COMPATIBILITY OF AIRCRAFT AND
RAWINSONDE MEASUREMENTS

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THESIS

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AND RAWINSONDE MEASUREMENTS

by

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and Rawinsonde Measurements

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ABSTRACT

Investigation of data obtained by aircraft during Project Rough Rider '71 reveals that aircraft navigation is unsatisfactory for meso-scale research on the convective cell scale. The established method for re-navigating the flights is modified to yield navigation errors of less than 0.1 nautical mile for most tracks when compared with entries in the navigator's log. It is shown that the corrections required are dependent on the height of the aircraft above the terrain, terrain slope and wind.

Meteorological parameters obtained from aircraft measurements are compared with rawinsonde measurements. These comparisons show that if appropriate corrections are applied, the data are useful for extending rawinsonde networks and defining spatial gradients of parameters between stations. Recommendations for determination of correction factors and suggestions for further research are made.

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LIST OF SYMBOLS AND ABBREVIATIONS

BOMEX	Barbados Oceanographic and Meteorological Experiment, May-July 1969
BOX	A type of winds calibration
DD	Wind direction (degrees)
DELDTC	Difference in distance traveled count between two observations
DTC	Distance traveled count
DTCCOR	Distance traveled count correction
EMB1	Experimental Meteorology Branch program one; a computer program used to process data obtained by aircraft
FF	Wind speed (knots)
GS	Ground speed
IFF	"Identification, Friend or Foe;" equipment installed in the aircraft which responds only to an interrogating signal; used for aircraft identification
NAVCOR	Navigation Correction program; a computer program used specifically for correcting navigation; a modified EMB1 program
NOAA	National Oceanographic and Atmospheric Administration
NM	Nautical mile(s)
NSSL	National Severe Storms Laboratory; one of the environmental research laboratories of NOAA
PLV	Probable Lower Value
PROV	Probable Range of Values
PST	Pair of Single Turns, a type of winds calibration

PUV	Probable Upper Value
RFF	Research Flight Facility
ST	Single Turn, a type of winds calibration
TACAN	Tactical Air Navigation, UHF navigation radio; provides azimuth and distance information
TAS	True airspeed
TASCOR	True airspeed correction, an additive correction in the TAS computation routine in the EMB1 program
TASCFR	True airspeed correction factor, a multiplicative correction in the TAS computation routine
VOR	VHF Omni Range; VHF navigation radio; provides azimuth information
VORTAC	VOR combined with TACAN, VHF/UHF navigation radio; provides azimuth and distance information

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I. INTRODUCTION

Each year the southern Great Plains states of Texas, Oklahoma and Kansas are the scene of some of the most violent weather known to man. Very small in relation to the synoptic systems with which they are frequently associated, squall lines, thunderstorms (often with hail) and tornadoes are triggered and advance across the countryside. In open country these phenomena are spectacular displays of the release of energy in the atmosphere. Over a farm or ranch or in populated areas these storms cause loss of life and damage in millions of dollars.

Endeavoring to unlock the mysteries of the formation of these mesoscale phenomena, the National Severe Storms Laboratory (NSSL) has been conducting mesoscale research for more than ten years. One of the environmental research laboratories of the National Oceanographic and Atmospheric Administration, NSSL is based in Norman, Oklahoma in a region known for its spring storms. A primary purpose of NSSL research is to provide guidance for the origination of timely and accurate forecasts of severe storm formation. The knowledge gained will perhaps lead to eventual modification of these phenomena to suppress or minimize their effects. A number of obstacles must be overcome before these goals can be realized. One step is devising the optimum use of aircraft in atmospheric

research; it is obvious that a mobile, guided platform configured for atmospheric observation is a most powerful and versatile tool.

The use of aircraft to conduct experiments in the atmosphere is nearly as old as aviation itself; atmospheric measurements were being taken by manned balloon as early as 1783. Most recent major contributions of aircraft to atmospheric research have been from the Barbados Oceanographic and Meteorological Experiment (BOMEX) in 1969, operations associated with the National Hurricane Research Laboratory, and flights in support of mesoscale research in the southern Great Plains. This study addresses the flight operations in support of Project Rough Rider '71.

The aims of Project Rough Rider '71 (Operations Plan 5-71, 1971) were to:

1. determine spatial and temporal variations along an east-west line in western Oklahoma during various weather conditions;

2. study flow patterns around isolated thunderstorms at various altitudes;

3. determine temperature, wind and humidity variations in the vicinity of radar "thin" lines and gust fronts;

4. compare rawinsonde and aircraft data sets.

This study is primarily directed to the fourth aim.

The investigation began with the goal of comparing rawinsonde and aircraft data to ascertain their compatibility and how to best use aircraft in future projects. Problems were uncovered associated

with the accuracy of aircraft navigation, and although much of this study has been directed toward navigation, the final goal of comparison of data was kept in mind.

Attempts to analyze mesoscale data have often produced questionable results. One reason for the difficulty is that the rawinsonde system was not designed for investigating mesoscale variations, and it is conceivable that errors in the measurements taken may be similar to the variations in the measured parameters. However, for this study it is assumed that both aircraft and rawinsonde instruments are capable of measuring important mesoscale variations. In developing mesoscale systems, spatial gradients are frequently highly non-linear. This is one area in which aircraft measurements could provide important information. For this investigation, in the absence of any qualifying detail, all spatial variations are considered linear.

The purposes of this study are to:

1. emphasize the navigation problems and describe how the navigation can be corrected for the data from Project Rough Rider '71;

2. compare the aircraft derived parameters of wind, temperature and mixing ratio with those of the rawinsonde;

3. describe how the navigation problems may be solved during future research projects in Oklahoma;

4. recommend the use of aircraft with a coordinated rawinsonde network.

II. INVESTIGATION OF PARAMETERS

A. DATA SOURCES

Aircraft data were acquired by a DC-6B aircraft (N6540C) of the NOAA Research Flight Facility (RFF). Of the 11 days of flight operations, four were selected which were expected to yield the greatest quantity of comparative data. During the four days of 5, 9, 17 and 18 May 1971 a total of 34 navigation tracks were investigated, representing about 18 hours of flight time. Twenty of the 34 navigation tracks were flown on an east-west line with 15 of those connecting the navigation points of Elk City Airport to the west, the Oklahoma City VORTAC and, to the east, the intersection of Interstate 40 and U. S. 69 on the southern outskirts of the town of Checotah. Figure 1 depicts the locations of these points which will be referred to as Elk City, OKC and Checotah respectively. Flights along this east-west line in each direction, at various pressure levels (most commonly 850 mb), provided the best opportunity to examine the measurements taken by the aircraft, while all 20 east-west tracks provided information regarding navigation.

Data available for processing was in the form of magnetic tapes (CONVT tapes) produced by the RFF CONVT program from the original data tapes. The RFF CONVT program checks the original data and discards records of incorrect length or records of poor quality (such

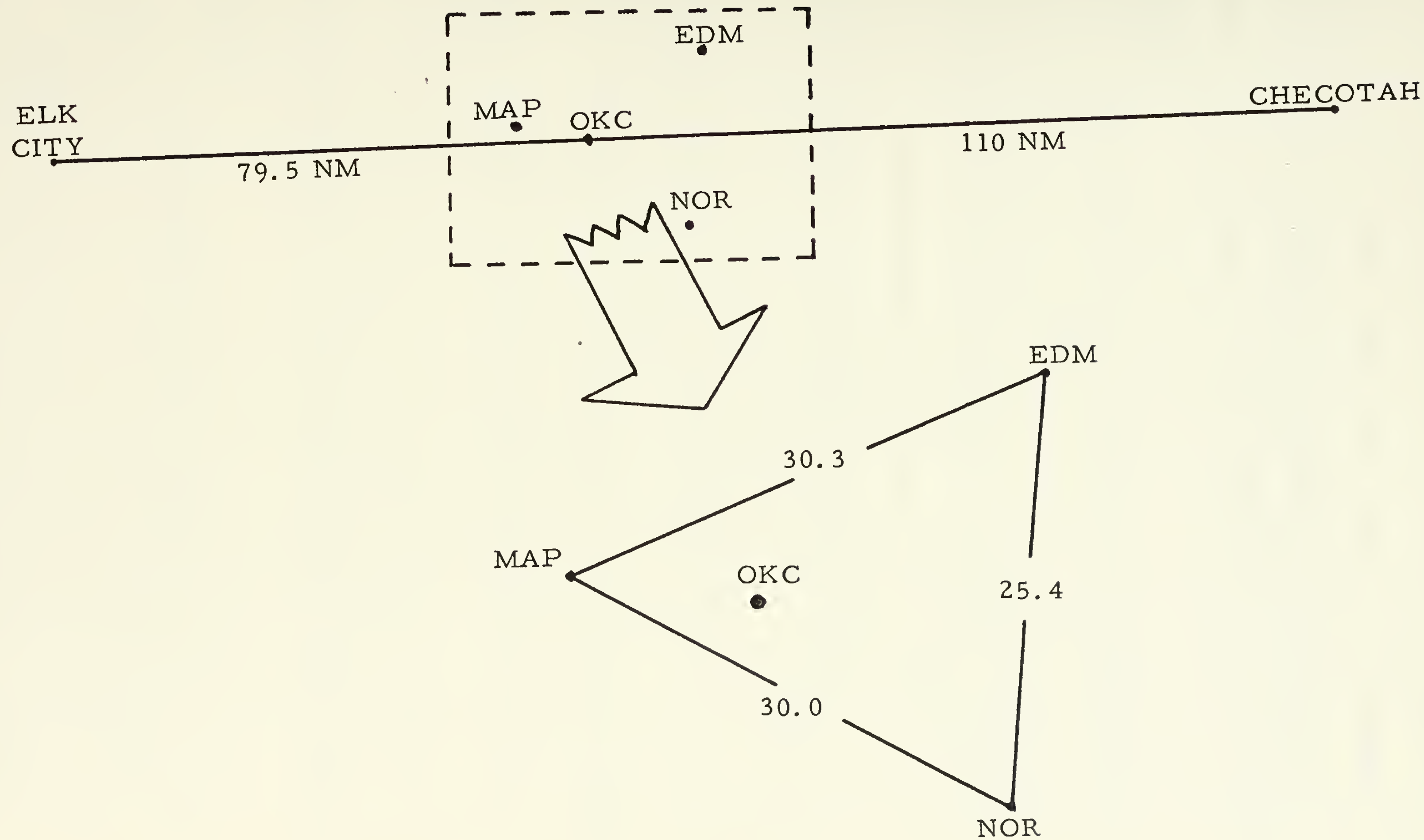

Figure 1. Primary fixes on east-west navigation tracks and expanded view of rawinsonde network (distances between stations in nautical miles).

as those which contain parity errors or invalid or illegal characters) (Friedman et al., 1969). The seven-channel CONVT tape data was converted to nine-channel for compatibility with the IBM 360 and was further processed using the RFF WINDS program and the REF EMB1 program.

The RFF WINDS program is designed to compute true airspeed and drift angle corrections which are then used to correct wind computations in subsequent data processing steps. True airspeed correction and drift angle correction are determined at desired pressure levels and at convenient geographic locations, usually at the beginning or ending of a navigation track. At each of these calibration stations on the days investigated, one of three types of calibrations was performed:

1. Single Turn (ST), ideally a two-minute leg of straight and level flight followed by a course reversal and another two-minute straight and level leg;

2. Pair of Single Turns (PST), ideally a single turn calibration followed by another with the base course rotated 90 degrees;

3. Box (BOX), ideally a pattern of four two-minute legs with each leg oriented 90 degrees from the adjacent legs.

The RFF WINDS program calculations rely on two basic assumptions, that the average ground speed for each leg is correct and that the wind during each calibration remains constant (Friedman

et al., 1969). An implicit assumption is that the true airspeed is constant throughout each calibration. Computed values of true airspeed correction and drift angle correction are incorporated into the RFF EMB1 program which provides re-navigation of the flight and yields printed output of a number of measured or calculated meteorological parameters.

Parameters selected for study include wind direction (DD), wind speed (FF), Rosemount temperature, vortex temperature, Infrared Hygrometer (IRH) mixing ratio, and Cambridge Systems (CSI) Dew Point Hygrometer mixing ratio. All values were observed or calculated each second and averaged over 60 seconds.

Rawinsonde data were obtained by a network of three stations, Mustang Airport (MAP), Edmond Airport (EDM) and Norman Airport (NRO), which are depicted in Figure 1. During the four selected days a total of 14 rawinsondes were launched while the aircraft was in the vicinity of the network. These data were from a series of digital listings from NSSL archive magnetic tapes produced by the Rawinsonde Reduction Program (Barnes et al., 1971). The parameters of temperature, relative humidity and pressure were recorded at significant levels as discussed by Barnes et al. (1971). Winds were determined at 150 meter height intervals from horizontal balloon displacement and averaged over 300 meters. Winds at significant levels were determined by a linear interpolation from 150-meter levels while temperature, relative humidity and pressure at 150-meter levels

were obtained by linear interpolation from significant levels. Other parameters were then computed from the interpolated values.

Comparative data points were established when the aircraft was in the vicinity of the rawinsonde network while rawinsondes were airborne. In general the procedure establishing primary comparative data points was to ascertain the aircraft position at the time the rawinsondes were at aircraft flight level. Secondary data points were located by determining aircraft positions at two-minute intervals each side of the primary data points until the aircraft was no longer in the network. Rawinsonde measurements were then linearly interpolated to the aircraft position. A total of 27 comparative data points were established, 18 of which were primary data points.

It is readily apparent that three dimensional location forms the basis of comparison of aircraft and rawinsonde data. Position in the vertical is the most accurate dimension, represented by pressure level in millibars. Accuracy of the aircraft pressure level was $\pm$ 0.5 mb (Friedman et al., 1970b), while that of the rawinsonde was $\pm$ 2.0 mb (Barnes et al., 1971). At 500 mb, where the greatest error would be present, (no operations were conducted above 500 mb) a 2.5 mb error represents approximately 120 feet. Rawinsonde position was provided by the GMD-1 rawinsonde system. Aircraft navigation is covered in detail in section IIB. Considering the time differential between secondary comparative data points and an associated rawinsonde observation, the greater the time differential the less valid the data

comparison. Although no upper limit was enforced, the time differential in all cases was no greater than 18 minutes.

On 17 May just prior to termination of flight operations, a simultaneous launch of rawinsondes was made at 2343Z designed to reach aircraft flight level of 500 mb at the aircraft's estimated time of arrival at OKC. Apparently endeavoring to expedite the final approach to Tinker AFB, the aircraft left 500 mb early and descended to just under 700 mb. The result was a comparative sounding, the rawinsonde ascending from 700 to 500 mb between 2351 and 2400Z while the aircraft descended from 500 to 700 mb between 2357 and 0009Z. This provided an excellent opportunity for comparative data study.

Figures A1 and A2 in Appendix A depict the locations of the majority of the comparative data points for 5 and 17 May. Appendix A consists of tables and figures containing data not presented in the body of the text.

B. NAVIGATION

1. Errors in Navigation

Fujita (1963) discussed the navigation errors encountered during the National Severe Storms Project, Spring 1962 flight operations. Since then two distinct steps have been taken to reduce navigation error, frequent entries on the navigator's log of aircraft position carefully determined by the aircraft navigator, and introduction of the RFF EMB1 computer program designed to re-navigate the flight

as well as calculate numerous meteorological parameters. While navigation errors have been significantly reduced there still remained the task of reducing navigation error to less than one nautical mile, recognized by Fujita (1963) as the requirement for investigation of phenomena on the scale of a cumulus cloud.

Figure 2 represents the distribution of navigation error of the 20 selected navigation tracks discussed earlier based on the navigation computed by the RFF EMB1 program without corrections. Each track could be identified by firm initial and terminal geographic positions as determined by the navigator. Each dot represents the terminal point of one computed navigation track relative to the navigator's terminal fix. The average total error of all 20 tracks was 2.0 nautical miles.

2. <u>RFF Calibration to Obtain True Airspeed and Drift Angle Correction</u>

The established procedure for obtaining navigation information is to apply the calculated true airspeed correction and drift angle correction from the RFF WINDS program to the RFF EMB1 program along with an initial latitude and longitude (Reber and Friedman, 1964 and Friedman et al., 1969). The EMB1 program employs the principle of dead-reckoning to determine aircraft position by translating the distance traveled between observations along a computed track into latitude and longitude coordinates. The author used the Navigation Correction (NAVCOR) program, which is basically the EMB1 program

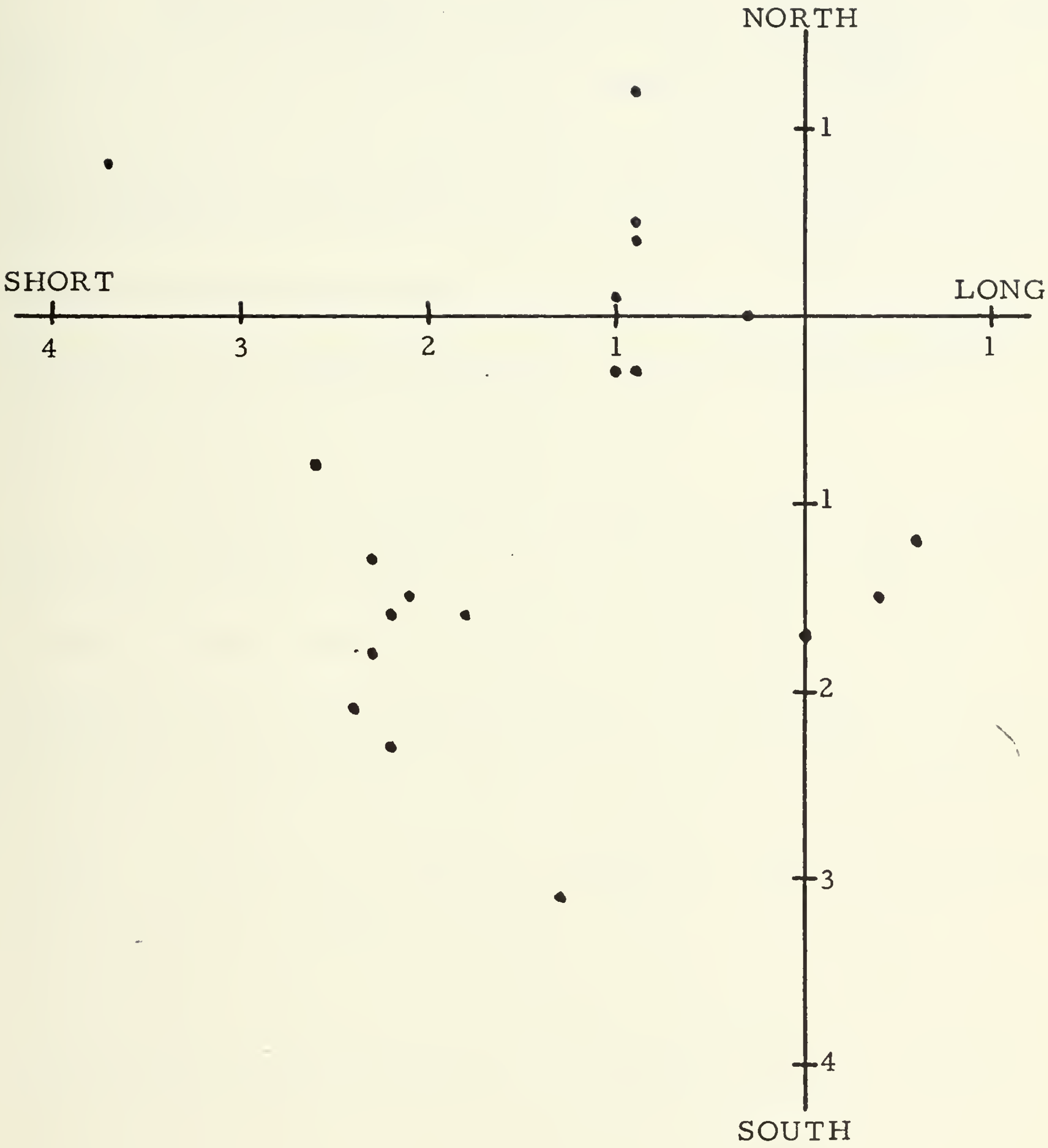

Figure 2. Distribution of navigation error for 20 east-west tracks with no navigation corrections applied (scale values in nautical miles).

modified for use in this study. The most important modifications will be discussed at the appropriate time.

The distribution of navigation error was investigated using the results of the NAVCOR program applying the corrections for true airspeed and drift angle obtained from the RFF WINDS program. The established procedure did not correct the navigation appreciably, the new average error being 1.8 nautical miles. Part of the difficulty appeared to lie in the determination of the true airspeed and drift angle corrections at the calibration stations.

Recall the assumptions that ground speed, as determined by the APN-82 Doppler system, is correct and that the wind and true airspeed remain constant throughout the calibration. Table 1 is a summary of the 13 calibration stations used to calculate true airspeed correction and drift angle correction. The set of columns labeled "Single Leg" shows the maximum variation of TAS, DD and FF along any one leg of a calibration station. The set labeled "Between Opposite Legs" describes the maximum variation of the same parameters between opposite legs of a calibration station. Variations of the magnitudes discovered are explained by the gustiness of the wind in the Oklahoma area during the spring of the year, a problem not usually encountered in the tropics where the calibration procedures have been used successfully (Reeves, 1971). In attempting to select calibration stations it was difficult to find series of legs with small

Station	Location	Level	Single Leg TAS	Single Leg DD	Single Leg FF	Between Opposite Legs TAS	Between Opposite Legs DD	Between Opposite Legs FF	TYPE CAL.
5-1	Checotah	850	13	11	7	17	14	8	PST
5-2	Elk City	700	12	15	15	23	20	15	PST
5-3	Checotah	500	10	8	7	21	13	11	PST
17-1	Elk City	850	9	11	8	10	22	9	ST
17-2	OKC	850	11	16	7	12	16	7	ST
17-3	Checotah	850	10	5	10	14	7	10	BOX
17-4	Checotah	700	5	9	6	12	17	12	BOX
17-5	Elk City	700	12	20	8	39	35	17	BOX
17-6	Elk City	500	10	9	11	27	29	14	BOX
18-1	Elk City	850	12	65	2	15	75	6	ST
18-2	Elk City	850	10	18	3	12	37	5	ST
18-3	Checotah	816	8	5	4	12	11	8	ST
18-4	Checotah	700	4	2	7	5	7	7	ST

Table 1. Variations of TAS, DD FF at each Calibration Station

variations, and frequently it was a case of accepting the variations or surrendering the calibration.

A factor contributing to navigation errors may be that all true airspeed corrections calculated were between 0.008 and 0.041 knots, which had negligible effects on the navigation. One might anticipate true airspeed corrections to be of the order of one rather than 10^{-2}.

3. Inclusion of a Distance Traveled Count Correction

Since the navigation tracks were oriented east-west, simple extrapolation to calculate a drift angle correction necessary to zero the latitude error was possible, but this procedure did little to solve the longitude error. An examination of Figure 2 revealed two significant features:

a. 15 of 20 tracks were south of the course;

b. 17 of 20 tracks were short of the fix.

It appeared that an increase in speed was necessary but simple additions of TAS and/or ground speed did not solve the problem. Latitude and longitude in the NAVCOR (also EMB1) program are determined from distance traveled and direction of flight. To make any change in longitude required a correction to the distance traveled (which results in a change of ground speed).

The distribution of navigation errors became even more significant when direction of flight was considered. Figure 3 represents the distribution of navigation errors (true airspeed and drift

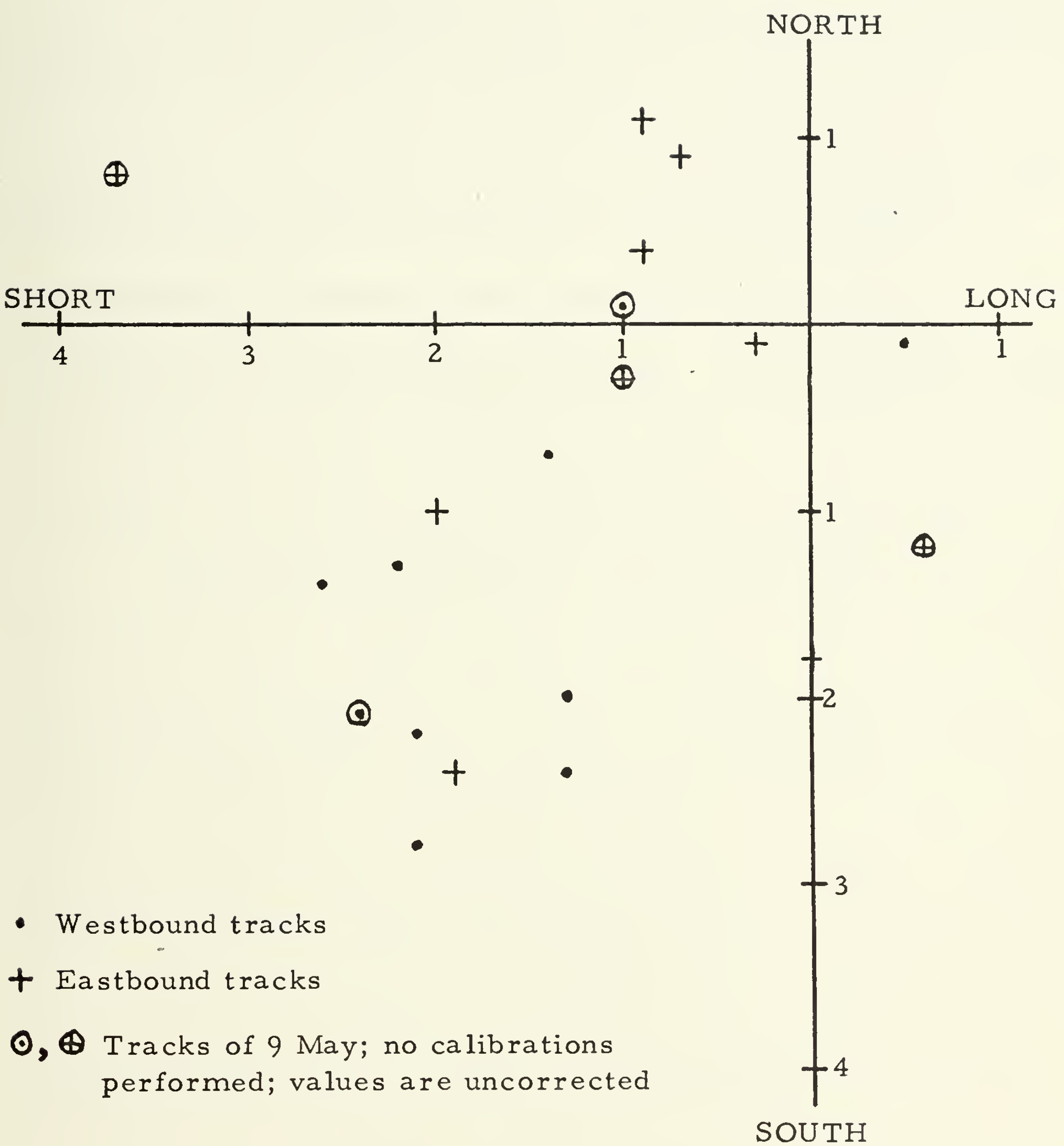

Figure 3. Distribution of navigation error for 20 east-west tracks with navigation corrections (scale values in nautical miles).

angle corrections from RFF WINDS program applied) for eastbound and westbound tracks. Each dot represents a westbound track, while a plus denotes an eastbound track. A dot or plus encircled represents a track conducted 9 May, a date when no calibrations for true airspeed or drift angle corrections were performed. Those five points then, are the uncorrected values repeated. Examination of Figure 3 revealed that westbound tracks tended to be further south and shorter of the terminal fix than eastbound tracks. The next step was to apply a correction to distance traveled along with the drift angle correction to attempt to simultaneously correct both latitude and longitude error.

In the EMB1 program, the only common factor to ground speed and longitude is the difference in distance traveled between two observations (DELDTC = DTD - DTC1). The NAVCOR program applied a multiplicative factor called distance traveled count correction (DTCCOR) to obtain a corrected difference (DELDTC = (DTC - DTC1) * DTCCOR), where DTCCOR was a discrete value for each track. Table A1 in Appendix A outlines the drift angle corrections computed by the WINDS program, the final drift angle and distance traveled count corrections necessary to correct latitude and longitude errors within 0.1 nautical mile for the four days used for this study. Figure 4 is a plot of distance traveled count corrections for several categories of tracks as indicated on the figure. The five east-west tracks of 9 May were excluded from the figure since, due to flight level or track differences, they did not fall among the described

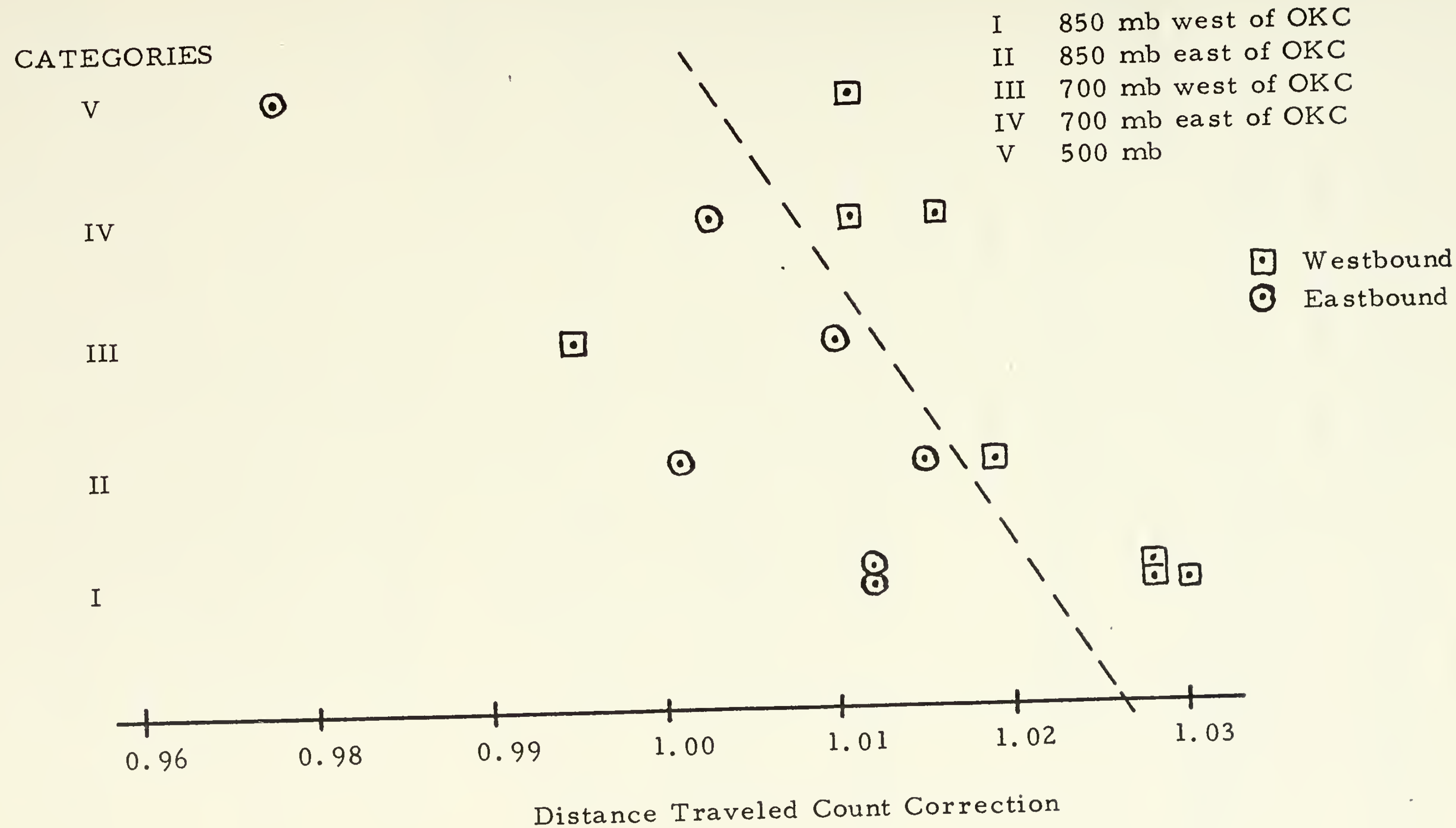

Figure 4. Distribution of distance traveled count correction correction for indicated categories of navigation tracks.

categories. Note that a dashed line has been added to accentuate the difference in corrections required for eastbound and westbound tracks. The demarcation was easily established, and only one point fails to appear on the appropriate side of the line.

From Figure 4 it can be concluded that the value of distance traveled count correction required to provide correct navigation appears to be a function of three variables:

a. height of aircraft above the terrain;

b. slope of the terrain;

c. wind.

The terrain elevations in the vicinity of Elk City, OKC and Checotah are 1981, 1353 and 610 feet respectively; thus westbound aircraft generally fly upslope. Wind direction varied between 180-240 degrees with speeds from five to 73 knots. While the relative importance of each individual variable is unknown, some qualitative conclusions can be drawn from Figure 4. It can be seen that the magnitude of the distance traveled count correction:

a. decreases as height above terrain increases;

b. is greater when the aircraft overflies rising terrain;

c. is greater when the aircraft proceeds into the wind.

4. <u>Navigation Tracks Other than East-West Tracks</u>

Although not illustrated in this report, some relatively large navigation errors were present in 14 of the 34 tracks. Two tracks flown 9 May, both circumnavigating thunderstorm cells, yielded

uncorrected errors of 4.2 and 2.5 nautical miles. Of most significance is that neither track could be corrected to yield navigation errors of less than 1.26 nautical miles. Indeed, to even approach that value required drift angle corrections greater than 10 degrees and distance traveled count modifications of 15 percent, magnitudes far greater than for any other track. With corrections of this size, midtrack navigation varied as much as 12 nautical miles from uncorrected navigation, and at one point corrected wind was calculated to be 273/24 while the uncorrected wind was 239/28. Whether the problems stemmed from the factors of terrain and wind compounded by long, shallow turns or by the airflow in the vicinity of the convective cells has not been determined. In any case, it is beyond the scope of this study to analyze the exact reasons why large navigational errors were associated with those two tracks. At this point it is sufficient to emphasize that the navigation problems associated with circumnavigation of convective cells were especially severe.

C. WIND

Fujita (1965) discussed the effects of precipitation, moving sea surface and normal (dry beam) operation of the APN-82 Dopper system on wind calculations. Wind information is positively dry beam at all comparative data points and since penetrations or overflights of precipitation areas were of short duration, all winds obtained during the four days under investigation are considered dry beam.

The established procedure for computing winds is the same as that for calculating navigation. When the correction to navigation was made in the form of a distance traveled count correction, a wind direction and speed could be calculated for a given and known geographical location, altitude and time. Consequently the established procedure was modified. The modification involved acceptance of a true airspeed correction from the RFF WINDS program and extrapolation of the drift angle correction and distance traveled count correction to achieve navigation accurate to within 0.1 nautical mile.

D. TEMPERATURE AND MIXING RATIO

Airborne temperature measuring systems included the Rosemount total temperature thermometer and the AN/AMQ-8 vortex thermometer. The only manipulation of temperature data was to add 1.1°C to the vortex temperature based on a comparison of Rosemount and vortex temperatures during the four days under investigation (from private communication with G. Conrad, RFF, dated 22 June 1971).

Mixing ratios from aircraft data were computed in the Meteorological Parameters program with navigation correction procedures employed. One mixing ratio was computed from relative humidity measurements taken by the Infrared Hygrometer (IRH). The Infrared Hygrometer uses the principle of vapor density measurements to determine relative humidity (Friedman et al., 1970a). The other mixing ratio from aircraft measurements was computed from relative humidity calculations based on dew point temperatures obtained by the

Cambridge Systems Instruments (CSI) Dew Point Hygrometer. Both mixing ratios were calculated as follows:

$$\text{Saturated Mixing Ratio} = \frac{0.622\ e_s}{p - e_s}$$

$$M = \text{Relative Humidity} * \text{Saturated Mixing Ratio}$$

Mixing ratios from rawinsonde data were calculated in the Rawinsonde Reduction Program in the same manner.

E. ERRORS

Those meteorological parameters investigated which were obtained from aircraft measurements and their respective errors (Reber and Friedman, 1964 and Friedman et al., 1970b) are listed in Table 2.

Table 3 lists those parameters acquired from rawinsonde measurements and their respective errors (Air Weather Service Technical Report 105-133, 1955; Clark, 1969; Barnes et al., 1971).

Probable range of values (PROV) was defined as the range of values a measured, observed or calculated parameter would assume if the error limits in Tables 2 and 3 were applied. Thus, the probable lower value (PLV) would be the observed value minus the error, the probable upper value (PUV) would be the observed value plus the error, and the probable range of values would be the difference between the probable upper and lower values (PROV = PUV - PLV). In the case of aircraft data the probable range of observed values are calculated in the Probable Range program, again the basic EMB1 program with navigation corrections, but with modified output. Probable range of

Table 2. Error in measurements of parameters from aircraft observations.

Parameter	Source	Error
DD	APN-82 Doppler Navigation System through METPAR* or NAVCOR** Program	$\pm (0.4 + \frac{150}{FF})$
FF	APN-82 Doppler Navigation System through METPAR or NAVCOR Program	$\pm$ 3 knots
TR	Rosemount temperature probe through METPAR Program	$\pm$ 1.0°C
TV	AMQ-8 vortex temperature probe through METPAR Program	$\pm$ 1.0°C
MI	IRH relative humidity sensor through METPAR Program	$\pm$ 5%
MC	CSI Dew Point Hygrometer through METPAR Program	$\pm$ 2.0°C

* Meteorological Parameters
** Navigation Correction

Table 3. Error in measurements of parameters from rawinsonde observations.

Parameter	Source	Error
DD	Digital listing of sounding from archive magnetic tape	$\pm$ 5°
FF	Digital listing of sounding from archive magnetic tape	$\pm$ 15%
T	Digital listing of sounding from archive magnetic tape	$\pm$ 1.0°C
M	Relative humidity through Rawinsonde Reduction Program	$\pm$ 5%

observed values for rawinsonde data were hand calculated using error limits given in Table 3.

III. RESULTS

A. NAVIGATION

Using the steps outlined in section IIC, the navigation for the 20 east-west tracks resulted in errors of less than 0.1 nautical mile compared with fixes provided by the navigator's log. The 20 tracks provided an excellent basis for navigational studies and yielded 27 comparative data points used for comparing rawinsonde and aircraft measurements.

B. WIND

Wind measurements and observations for the 27 comparative data points were tabulated and appear in Tables A2a-d in Appendix A. All values were plotted for analysis, and Figures A3a and A3b are wind directions and speeds for seven representative points. The analysis of wind direction and speed was a comparison of rawinsonde winds with aircraft winds resulting from each of the following correction schemes:

1. uncorrected navigation;

2. navigation corrections based on application of drift angle correction and true airspeed correction from RFF WINDS program;

3. corrections based on application of true airspeed correction from RFF WINDS program with extrapolated values of drift angle correction and distance traveled count correction;

4. navigation corrections as in three above but with a true airspeed correction factor equal to the distance traveled count correction.

Using the rawinsonde winds as the basis for comparison, the aircraft winds associated with uncorrected navigation had root mean square differences of 4.1 degrees and 5.4 knots for the 27 comparative data points. Applying the corrections from the RFF WINDS program improved the results to 3.3 degrees and 4.6 knots. With the navigation corrected by extrapolated values of drift angle and distance traveled count correction the comparison degraded considerably to RMS differences of 6.6 degrees and 4.2 knots.

This was the point at which the investigation of winds should have been completed. Each calculation of wind was associated with a time, a correct geographic position and an altitude. A remaining problem was that the winds compared most unfavorably with rawinsonde winds, but further, the differences displayed a pattern which strongly suggested that these aircraft winds were incorrect.

The only factor present in the scheme producing correct navigation that was not present in the first two was a distance traveled count correction. Translated into vectors this correction produced a change in the magnitude of the ground speed vector as large as three percent. In order to retain the wind vectors obtained when using only corrections from the RFF WINDS program, it was necessary to change the true airspeed vector by an amount equal to the change in ground speed.

The most correct means of applying the true airspeed correction would be to make the factor equal to the change in ground speed (in knots) and apply the factor as an additive term in the true airspeed computation routine. This procedure, however, required extensive reprogramming, and a simpler method was adopted. The true airspeed correction factor was made equal to the distance traveled count correction; both were then percentage terms and applied as multiplicative factors. It can be seen that the only time this method would be exactly correct would be when the ground speed and the true airspeed were equal. If the former method were used, the root mean square differences would be nearly identical to those obtained by applying RFF WINDS corrections only. The latter method yielded RMS differences of 3.5 degrees and 4.1 knots. The changes in ground speed and true airspeed resulting from the application of the above factors are tabulated in the right hand columns of Table A1 in Appendix A.

It is perhaps discomforting that so many corrections are required, but in the final analysis the choice is this: to have favorably comparable winds while accepting navigation errors of up to 3.8 nautical miles, or to apply the necessary correction factors and obtain equally favorable winds with navigation errors of less than 0.1 nautical mile.

Since direction of flight seemed to have such an important effect on navigation, it was suspected that the wind as measured by the aircraft would be similarly affected. To examine the effects of

direction of flight on winds, the navigation tracks were studied to locate instances where consecutive navigation tracks coincided with the same geographical path in opposite directions. The stipulation on time was that the second track must begin within minutes after the end of the first track. Only three such instances occurred, and their characteristics are portrayed in Table A3 in Appendix A. Figures 5a-c are plots of DD and FF for aircraft winds (all corrections applied) along the opposite tracks.

From Figures 5a-c it is evident that aircraft winds for eastbound tracks were clockwise and stronger than for westbound tracks. This suggests that the corrections used to produce these winds created an artificial wind shift. Figures 6a-c illustrate winds for the same tracks obtained before any navigation correction was applied. Although wind directions for eastbound and westbound tracks nearly agreed for the 9 and 17 May cases, those of 5 May were definitely more clockwise for the eastbound track, and the winds for all three cases were stronger for eastbound tracks than for westbound. Thus, application of navigation correction factors merely accentuated an artificial wind shift already present.

Another illustration of the effects discussed above is shown in the plotted winds for the comparative sounding in Figure 7. Shown are rawinsonde winds and aircraft winds associated with uncorrected navigation and with fully corrected navigation; aircraft winds from the other navigation schemes generally fall within the envelope described

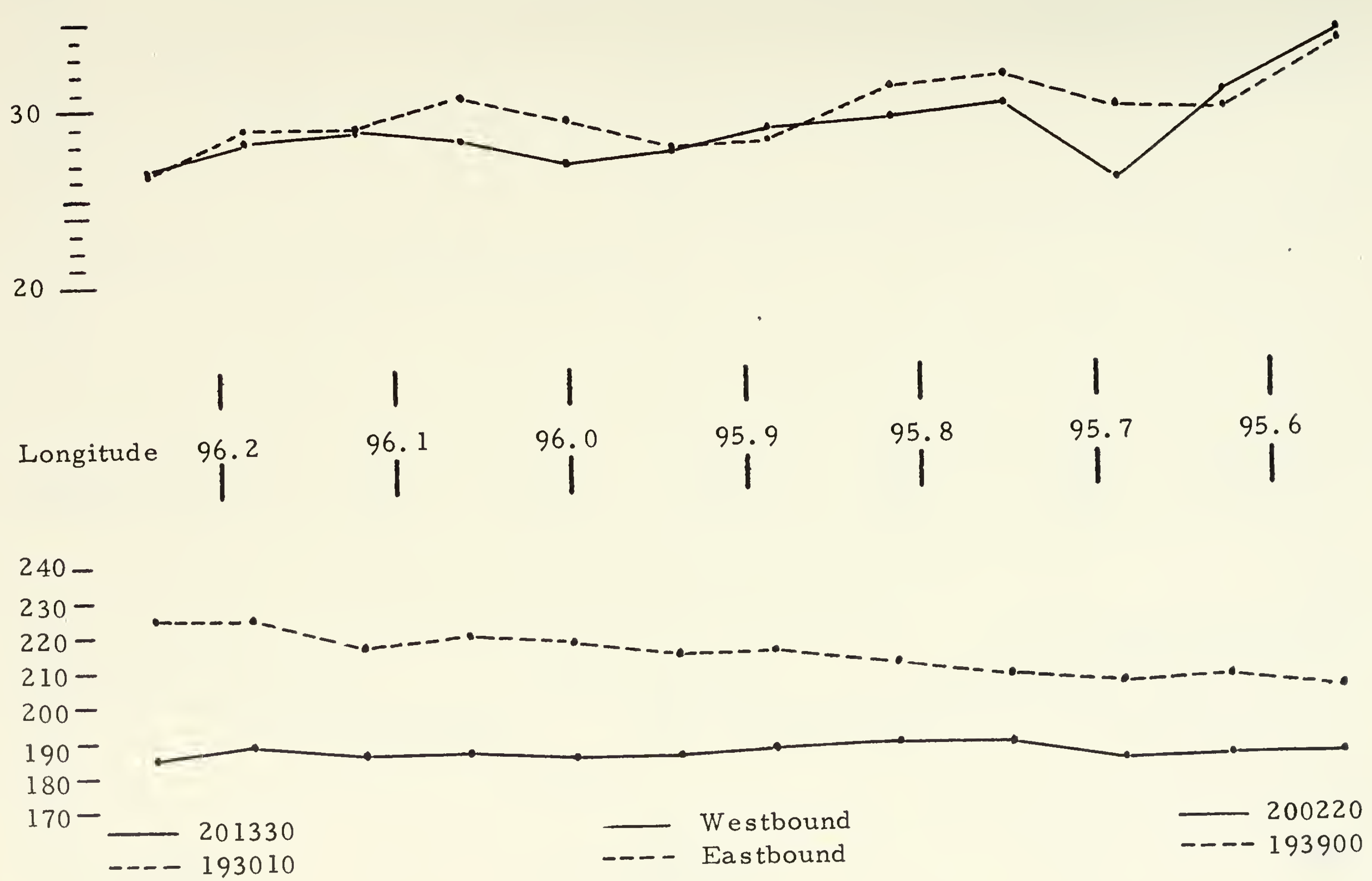

Figure 5a. Comparison of wind direction and speed (navigation corrected) for opposite direction coincident tracks of 5 May 1971.

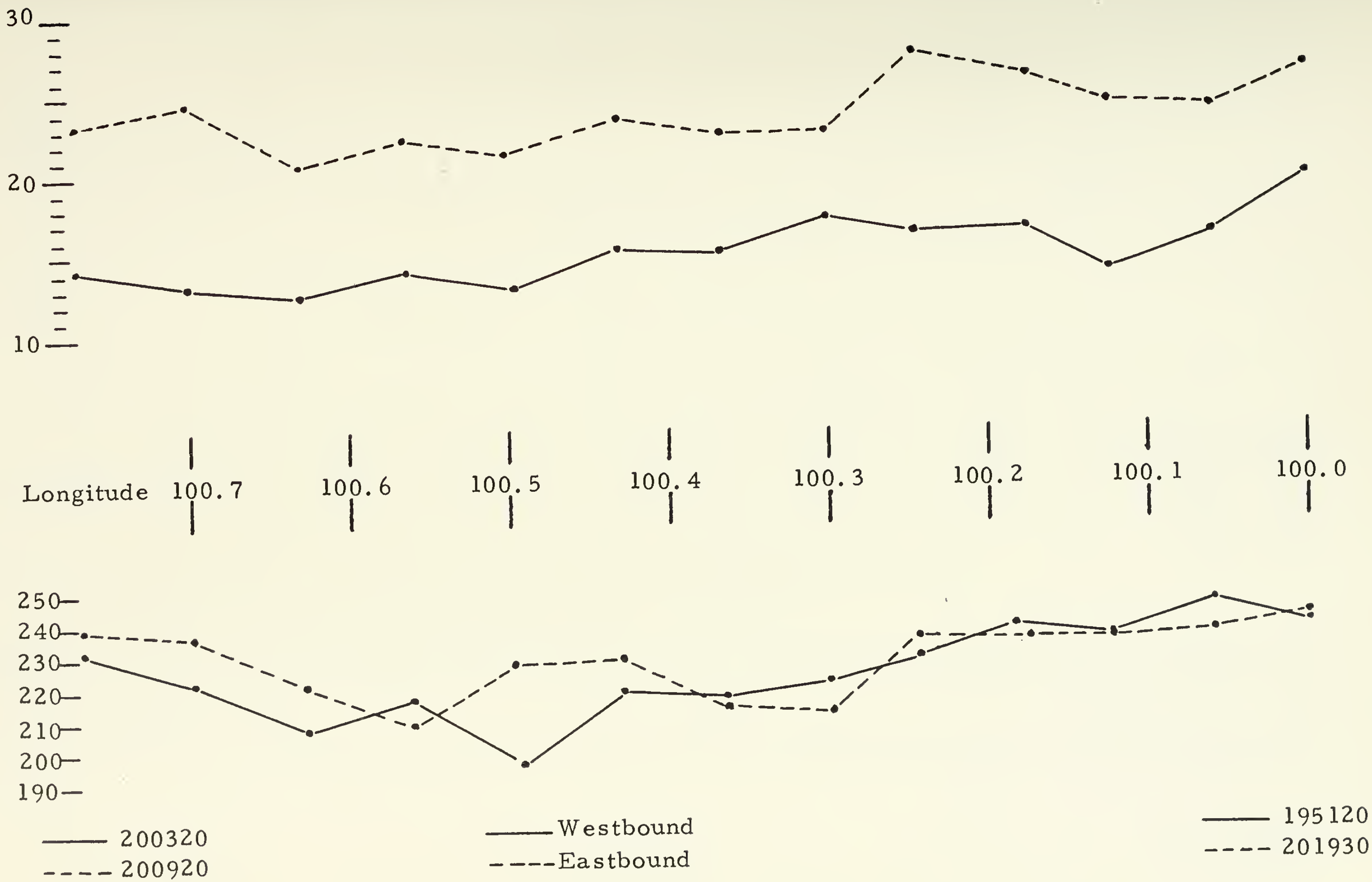

Figure 5b. Comparison of wind direction and speed (navigation corrected) for opposite direction coincident tracks of 9 May 1971.

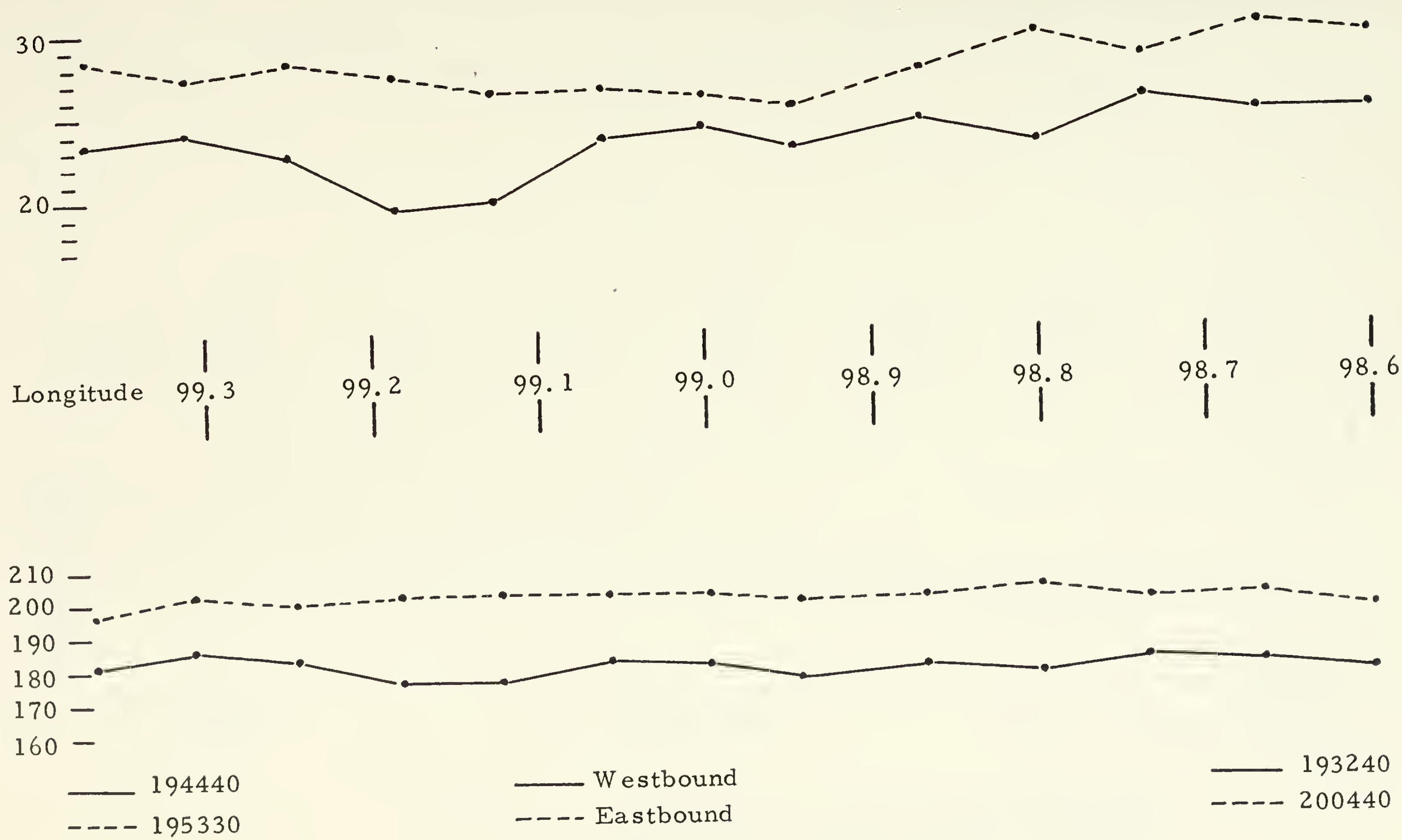

Figure 5c. Comparison of wind direction and speed (navigation corrected) for opposite direction coincident tracks of 17 May 1971.

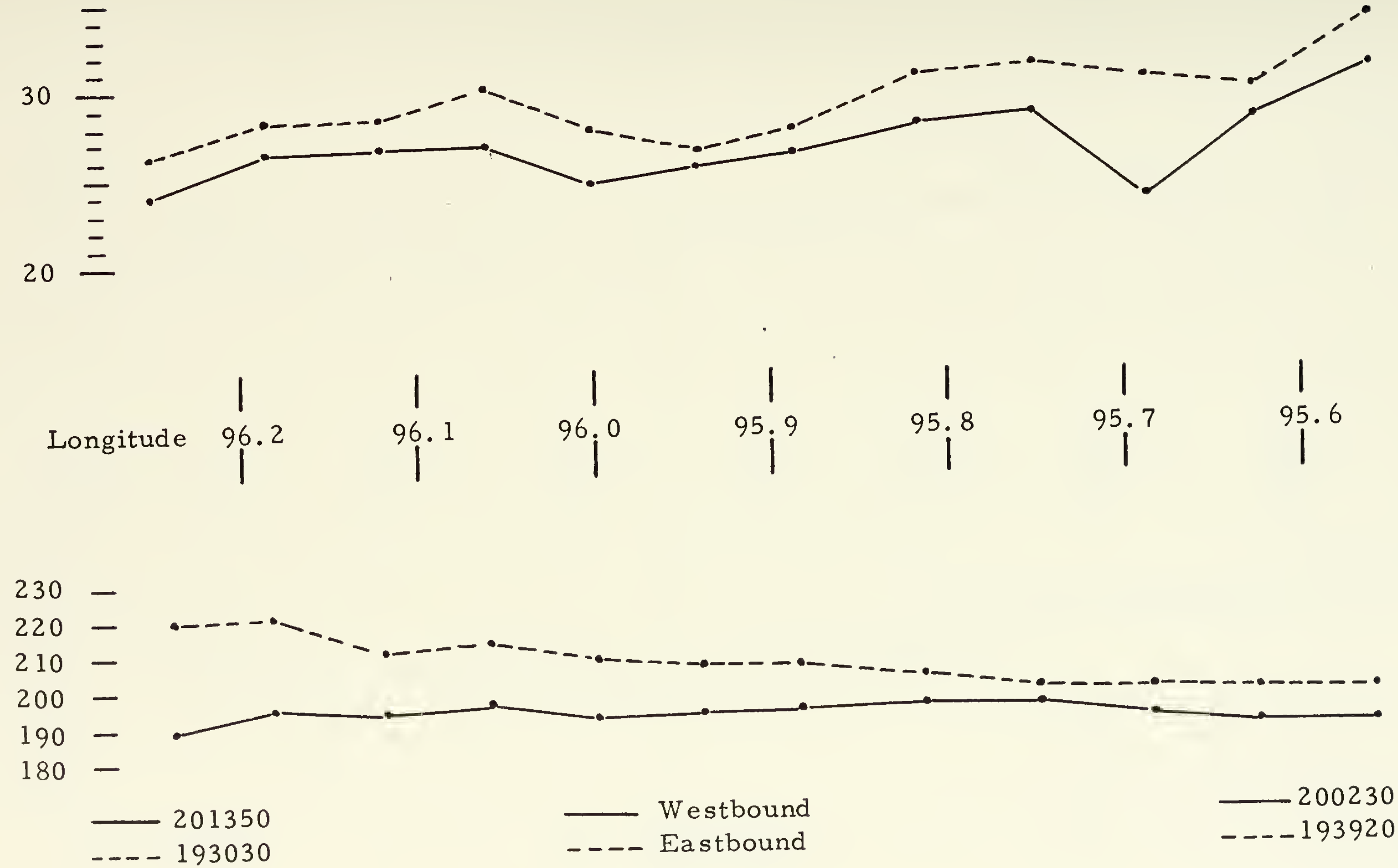

Figure 6a. Comparison of wind direction and speed (navigation uncorrected) for opposite direction coincident tracks of 5 May 1971.

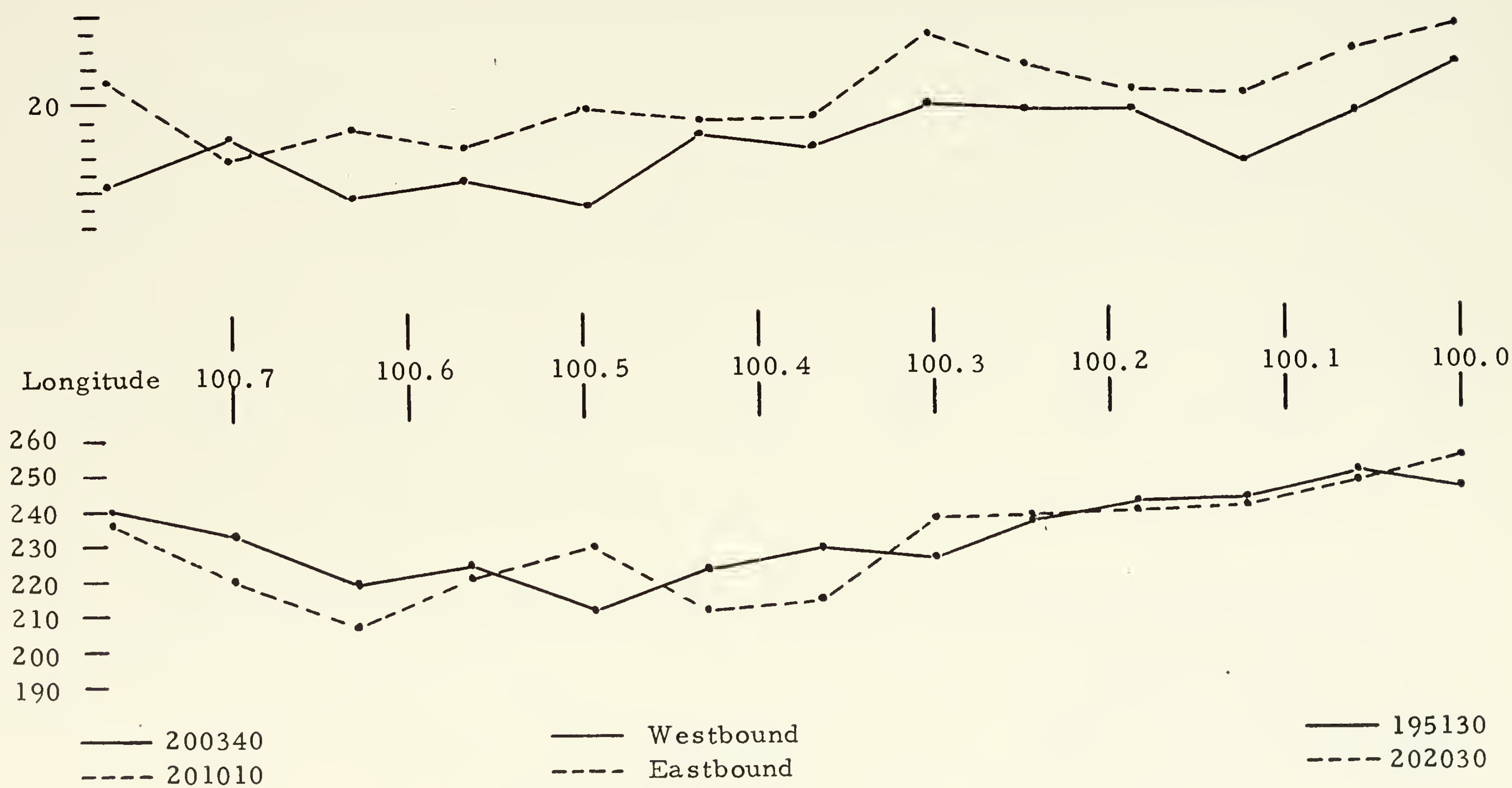

Figure 6b. Comparison of wind direction and speed (navigation uncorrected) for opposite direction coincident tracks of 9 May 1971.

Figure 6c. Comparison of wind direction and speed (navigation uncorrected) for opposite direction coincident tracks of 17 May 1971.

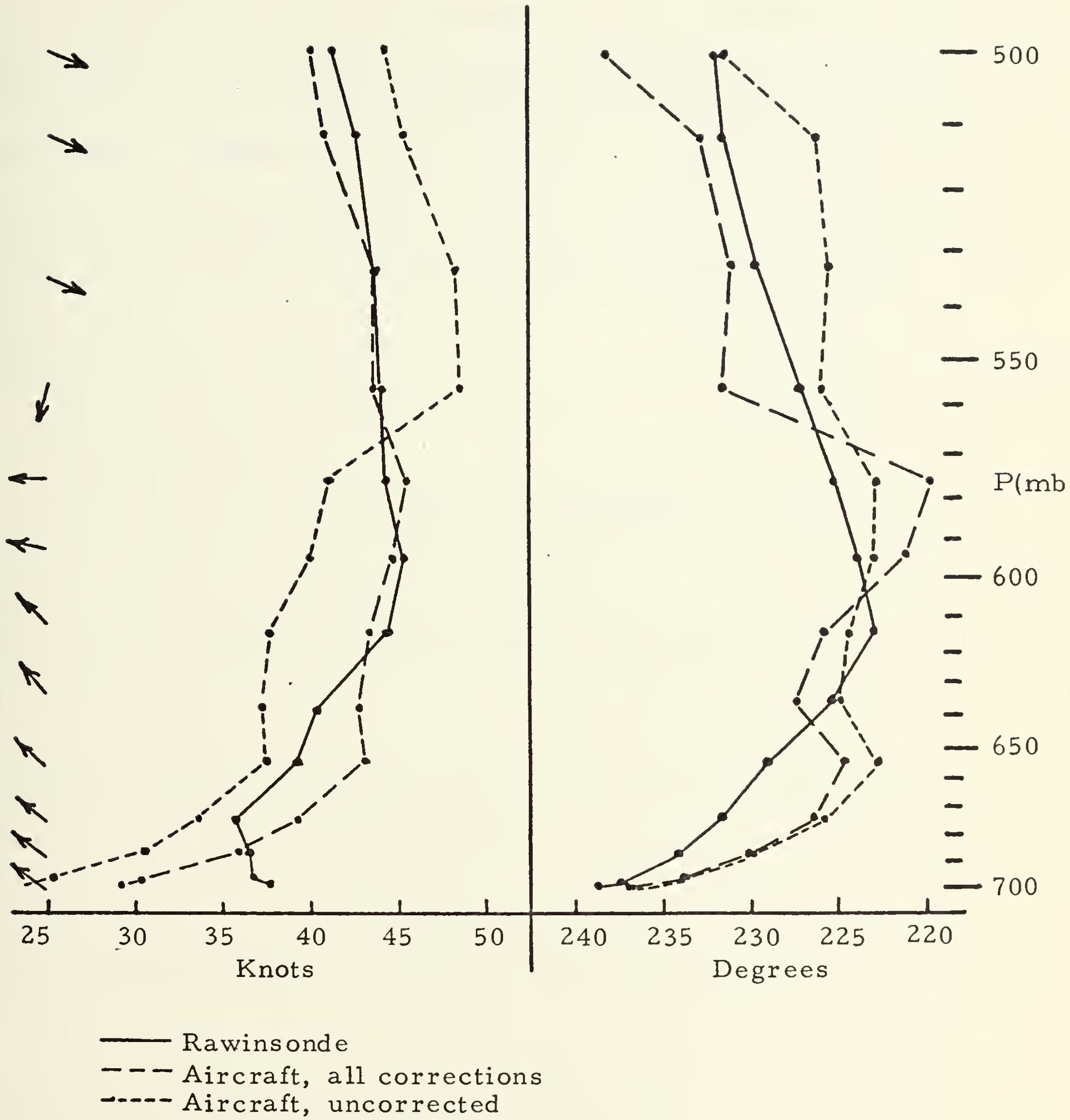

Figure 7. Comparative sounding of rawinsonde and aircraft winds 700-500 mb 17 May 1971.

by the two plotted winds. Figure 7 also provides a visual comparison of aircraft winds with rawinsonde winds at typical comparative data points. The arrows on the left hand side of the illustration portray the direction of flight as the aircraft descended from 500 mb. As the aircraft turned from eastbound to westbound between 550 and 575 mb a definite counterclockwise rotation and general weakening of the winds occurred.

C. TEMPERATURE

Temperature measurements and observations for the 27 comparative data points were tabulated and plotted for analysis. Tables A4a and A4b in Appendix A list the rawinsonde temperatures, vortex temperatures and Rosemount temperatures and their probable range of values for all the comparative data points. Seven representative points are plotted in Figure A4 (Appendix A). There was rather close agreement among the temperatures, particularly at the primary data points, but temperature comparisons deteriorated as the time between the primary and secondary data points increased. The causes are unknown, but two distinct possibilities are dynamic changes during the intervening period and nonlinearity of the temperature distribution in mesoscale systems.

For the 18 primary data points, 56 percent of the vortex temperatures (with correction discussed in section IID) and 67 percent of the Rosemount temperatures were within one degree C of the

rawinsonde measurements, while 95 and 100 percent respectively were within two degrees. Average absolute differences between rawinsonde and vortex and Rosemount temperatures were 1.1 and 1.0 degrees respectively, while root mean square differences were 1.3 and 1.4 degrees. These results indicate that although the Rosemount temperature was generally in better agreement with the rawinsonde, some departures were relatively large.

Figure 8 is a plot of rawinsonde temperature, vortex temperature and Rosemount temperature for the comparative sounding of 17 May. In this sounding the Rosemount temperature was within one degree of the rawinsonde temperature for most of the sounding. It should be noted that temperature discrepancies can be corrected by careful calibration before flight and/or by correction factors applied during data processing. If one considers the error in each system, both vortex and Rosemount temperatures compared quite favorably with rawinsonde temperatures during the four days under investigation.

D. MIXING RATIO

Undoubtedly the least accurate of the parameters under investigation, mixing ratio is not directly measured but is a function of relative humidity, the measurement of which is not especially accurate. Calculated mixing ratios from relative humidites measured by rawinsonde, Infrared Hygrometer (IRH) and Cambridge Systems Dew Point Hygrometer (CSI) for the 27 comparative data points were tabulated

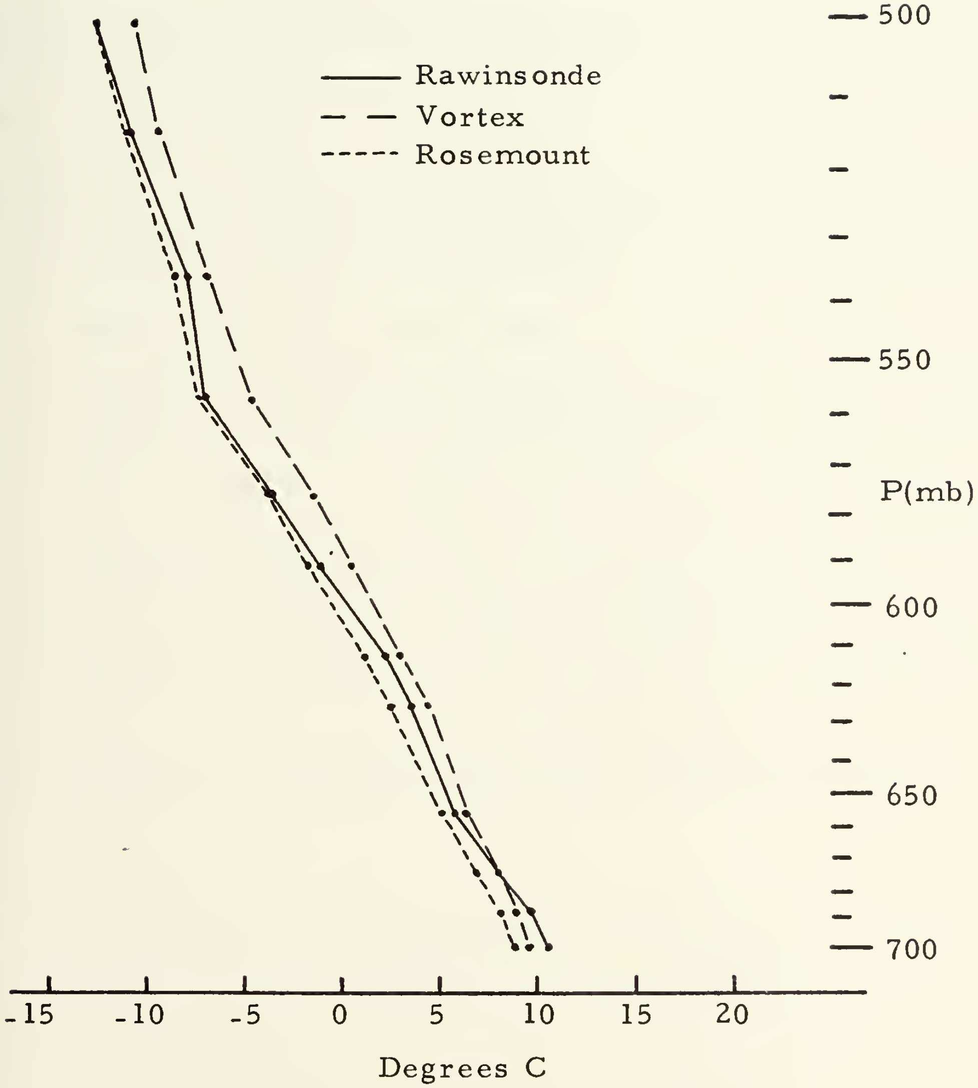

Figure 8. Comparative sounding of rawinsonde and aircraft temperatures 700-500 mb 17 May 1971.

and plotted for analysis. Tables A5a and A5b in Appendix A present mixing ratios and their probable ranges of values for all comparative data points, seven selected data points are presented in Figure A5, also in Appendix A. As with temperature, mixing ratio comparisons degenerated for the secondary data points. Probable ranges were computed as described in Tables 2 and 3 and essentially represent the values the rawinsonde and IRH mixing ratios would assume with a plus and minus five percent relative humidity error, and the values the CSI mixing ratio would assume with a $\pm$ 2.0°C dew point temperature error, while all other factors remained constant. The probable ranges varied with the amount of moisture in the air, with rawinsonde mixing ratios having probable ranges of 0.3 gm/kgm in drier air and 2.2 gm/kgm in more moist air. Cambridge Systems Hygrometer mixing ratio probable ranges were from 0.5 gm/kgm to 2.7 gm/kgm, while IRH mixing ratio probable ranges were relatively narrow, 0.1 to 1.0 gm/kgm.

For the 18 primary data points, mixing ratios from aircraft data were within the stated error limits of the rawinsonde mixing ratios in only 33 percent of the cases. The root mean square differences between rawinsonde mixing ratio and IRH and CSI mixing ratios were 1.73 and 1.92 gm/kgm respectively. The average absolute differences were 1.32 and 1.48 gm/kgm respectively, which appeared to be acceptable until it was discovered that the average of the probable range of values for the rawinsonde mixing ratios was only 0.88 gm/kgm.

A plot of the values of mixing ratios acquired in the comparative sounding of 17 May is displayed in Figure 9. That the rawinsonde and aircraft curves bear so little resemblance may be attributed to the nonlinearity of the parameters under consideration, the time differences between rawinsonde and aircraft measurements and the smoothing of the aircraft data during processing. During the aircraft's descent from 500 to 700 mb, descent rates as high as 1000 feet per minute were recorded. With aircraft data being averaged over a 60-second period, smoothing conceivably took place over as much as 30 mb.

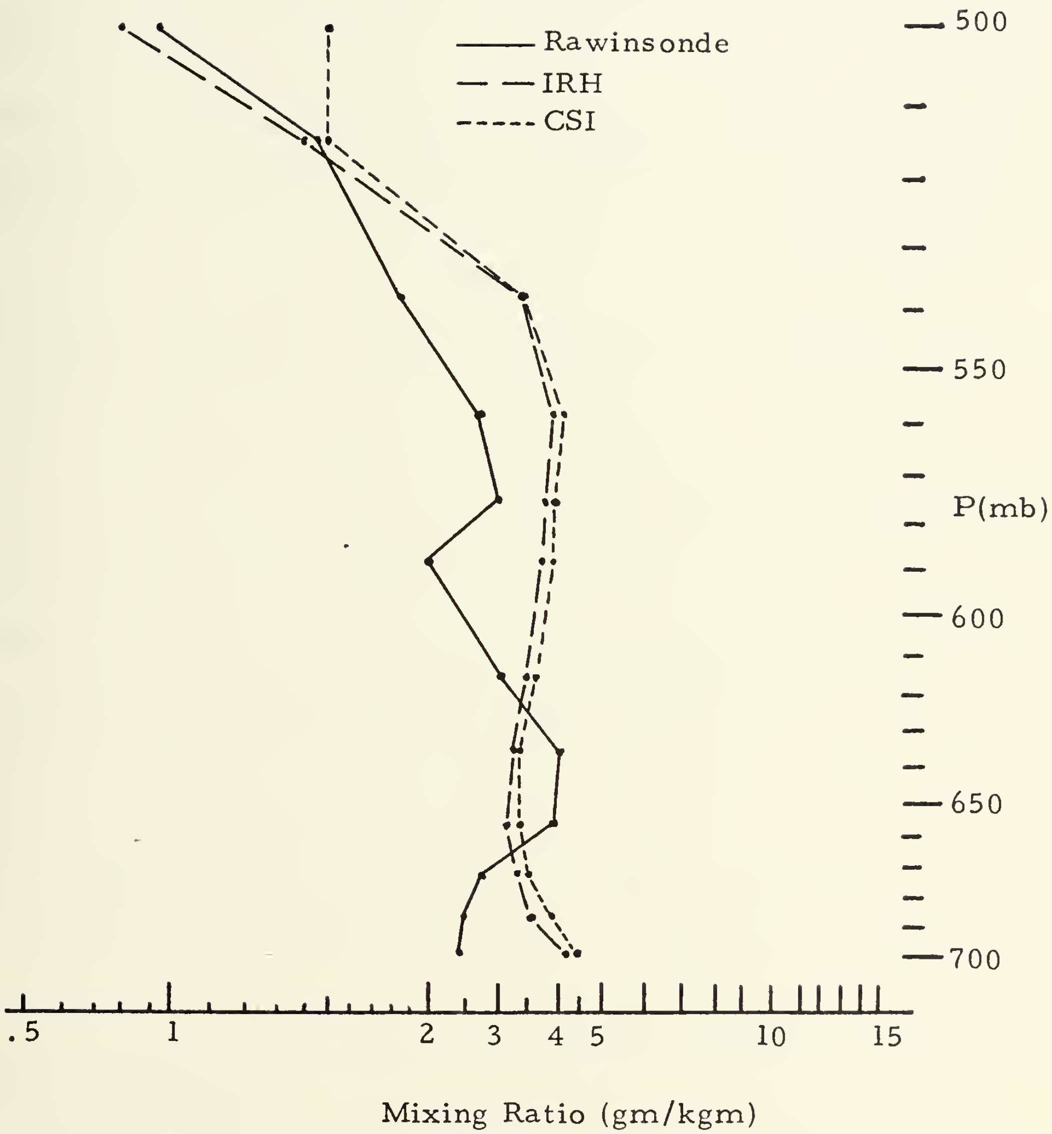

Figure 9. Comparative sounding of mixing ratios from rawinsonde and aircraft measurements 700-500 mb 17 May 1971.

IV. CONCLUSIONS

A. NAVIGATION

Correct navigation was the single most difficult and most serious problem investigated. In its present state the AN/APN-82 Doppler Navigation System over land provides neither the accuracy required for complete mesoscale research nor accuracy within the published system limits. In cases involving strictly east-west tracks the navigation could be corrected in the data processing step with some rather simple corrective factors. The corrections were not inexpensive however, since five to six computer runs of the NAVCOR program were required to reduce the navigation error within 0.1 nautical mile. Although none were investigated, it is probable that north-south oriented tracks could have been similarly corrected. Although not specifically studied, tracks in directions other than east-west (or north-south) were more difficult to correct. Two tracks (which circumnavigated thunderstorm cells) could not be corrected to the desired accuracy, and the remaining tracks required an average of eight computer runs.

Films of radar scope photographs were studied in an effort to help solve the navigation problems of other than east-west tracks, but this proved most unsatisfactory for the following reasons:

1. the radar scope photographed was not the one being used for air traffic control and lacked identifying geographic or navigational fixes;

2. the IFF feature[1] was not always operating, or was lost below the radar horizon;

3. on the 125 NM range, aircraft distance from the radar site could be determined at best only to the nearest mile;

4. azimuth markers to east, west, north and south did not appear on the photographs making aircraft bearing extremely difficult to determine;

5. six primary and three secondary airways converge on the Oklahoma City VORTAC, two of which nearly coincided with the east-west tracks, making identification of the project aircraft difficult;

6. clutter in the center of the scope extended to 10-12 nautical miles from the radar site so that when the aircraft was near the site its position could not be determined;

7. compatible equipment for viewing and copying the films was not available.

It is certain from the results of this investigation that the Doppler navigation is dependent on height above the terrain and direction of flight associated with terrain slope and wind direction. Accuracy

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[1] "Identification, Friend or Foe;" equipment installed in the aircraft which responds only to an interrogating signal; used for aircraft identification.

figures presented (Reber and Friedman, 1964; Friedman et al., 1970b; Meyer, Ed., 1971) do not specifically address these factors, but it is suspected that the accuracies presented are for over water or relatively flat terrain. The relative importance of these factors must be resolved if the Research Flight Facility is scheduled to participate in the Wave Momentum Flux Experiment (WAMFLEX) in 1973. Based on the results of this investigation, RFF equipment may not be able to meet all of the accuracy criteria delineated in the WAMFLEX preliminary plan (Lilly, 1972).

For the 20 east-west tracks selected, the navigation could be corrected to within 0.1 nautical mile of the position indicated in the navigator's log. The application of true airspeed corrections, drift angle and distance traveled count corrections with the NAVCOR program was considered to be a valid scheme for correcting the navigation.

B. WIND

A comparison of rawinsonde winds was conducted with winds derived from the APN-82 Doppler system. Aircraft winds calculated included winds from uncorrected navigation, from navigation corrected only for true airspeed and drift angle corrections provided by the RFF WINDS program, from navigation corrected with true airspeed corrections from the RFF WINDS program and extrapolated values of drift angle and distance traveled count corrections, and, finally, from

navigation corrected with true airspeed corrections from the RFF WINDS program, extrapolated values of drift angle and distance traveled count corrections and a true airspeed correction factor equal to the distance traveled count correction.

A comparison of aircraft winds with rawinsonde winds was performed using root mean square differences. The two best comparisons with rawinsonde winds were either from winds associated with navigation corrections provided by the RFF WINDS program only or from winds associated with navigation in which all correction factors were applied, and both of these aircraft winds were equally favorable. In spite of the numerous corrections applied, the latter wind should be accepted as the correct aircraft wind since it is associated with correct navigation whereas the former is not.

The average wind speed for the 27 comparative data points was 36 knots, therefore the average measurement error according to Table 3 was 5.4 knots. Considering the anticipated rawinsonde wind errors of five degrees in direction and 5.4 knots in speed, it can be seen that the root mean square differences between the rawinsonde and final aircraft measurements of 3.5 degrees and 4.1 knots are within the expected accuracy of the rawinsonde system. While these are encouraging results, it should be remembered that aircraft winds were averaged over horizontal distances of 2.5-4.0 nautical miles and essentially zero vertical displacement, while the rawinsonde

winds were averaged over a sloping path corresponding to approximately 0.5 nautical miles horizontal and 300 meter (984 feet) vertical displacements.

Comparing winds observed on opposite direction coincident tracks, it was observed that winds associated with fully corrected navigation appeared to produce an artificial wind shift. Further investigation revealed that the wind shift also occurred with no navigation corrections, although application of corrections accentuated the apparent wind change. It is suggested that the artificial wind shift is inherent in the APN-82 Doppler system lending support to the hypothesis that direction of aircraft flight with respect to wind and terrain is important. Because navigation and wind calculations are interdependent, it is likely that the solution of the navigation problems could also correct wind discrepancies.

The winds derived compare favorably enough that aircraft winds may be used for any calculations in which rawinsonde winds are used.

C. TEMPERATURE AND MIXING RATIO

After an analysis of both vortex and Rosemount temperatures for the four days investigated, a 1.1 degree correction was incorporated in the data processing programs. In view of the results it is questionable whether any correction was necessary. The data for the four days were reprocessed with no correction to the vortex temperature, and for the 18 primary comparative data points the average and RMS

differences were 1.02 and 1.27 degrees respectively, compared with 1.09 and 1.25 degrees with the 1.1 degree correction. Although the effects of nonlinear distribution in space were evident in measurements at secondary comparative data points, comparisons at primary data points yielded excellent results.

Comparison of the aircraft mixing ratios calculated from measurements of the Infrared Hygrometer and the CSI Dew Point Hygrometer with rawinsonde mixing ratios were less than satisfactory. The average absolute differences between rawinsonde mixing ratios and IRH and CSI mixing ratios were nearly twice as great as the calculated error in the rawinsonde mixing ratio due to expected errors in measurement. The major portion of mixing ratio errors stems from the relative humidity determination, and a one degree temperature error has a negligible effect. Mixing ratio comparisons also suffered the same degeneration at the secondary data points as was experienced with temperature measurements. A more careful and thorough study of Rough Rider '71 mixing ratio data is warranted prior to any analytical use of the data.

V. RECOMMENDATIONS FOR FURTHER RESEARCH

While the spirit and enthusiasm of the well-trained RFF flight crews are known and appreciated, their professionalism cannot always overcome any deficiencies in the equipment installed in the research aircraft. In the case of aircraft navigation, the AN/APN-82 Doppler Navigation System has been shown to be inadequate for the type of research conducted during Project Rough Rider '71. One solution to the navigation problems would be to invest in a new Doppler navigation system. Coupling the new system with an inertial platform would provide an extremely accurate navigation and wind computing system (Meyer, Ed., 1971), which would also lend to RFF a versatility for data acquisition heretofore unknown. Bowing to the realities of life where funds for research are short enough, not to mention funds for new equipment, it is suggested that the means may be available for devising an interim scheme to correct the navigation. If such a scheme fails, a new navigation system is a requirement if the full potential of the Research Flight Facility resources are to be realized.

The scheme in general would provide for the determination of correction factors for the effects of aircraft height above the terrain, terrain slope and wind. It would require a total of 7-11 four-hour flights. Three to five flights would be conducted over very flat, level

terrain, and four to six more in the Oklahoma City area. The former set of flights would involve flying the perimeter of a square no less than 50 nautical miles on a side with the sides oriented east-west and north-south. The corner points must be identifiable navigation fixes, either geographic or electronic, or two opposite corners may be VOR, VORTAC or TACAN stations. Each flight would consist of flying the perimeter one complete circuit at 850 mb followed by circuits at 700 mb and 500 mb. Each leg must begin and end at a corner fix, and each flight should be conducted with different wind conditions.

The flights over Oklahoma would be conducted similarly. One recommended square (Figure 10) would have the Hobart VOR (HBR) and the Kingfisher VORTAC (IFI) at the southwest and northeast corners respectively. The northwest and southeast corners would be about four miles northwest of Anthon and at Farwell respectively. It is not an exact square with the east-west legs 52 nautical miles long and the north-south legs 56 nautical miles, but it overlies variable terrain and is clear of restricted areas and Air Force training areas.

On alternate days the flights would be conducted around the perimeter in opposite directions rather than one direction for all flights. Data would be taken as for any other project flight. Analysis of the 11 flights should produce factors for correcting for terrain slope, height and wind and the variability of these factors. Subsequent flights then need only a knowledge of the terrain, planned flight level and an estimate of the upper level winds.

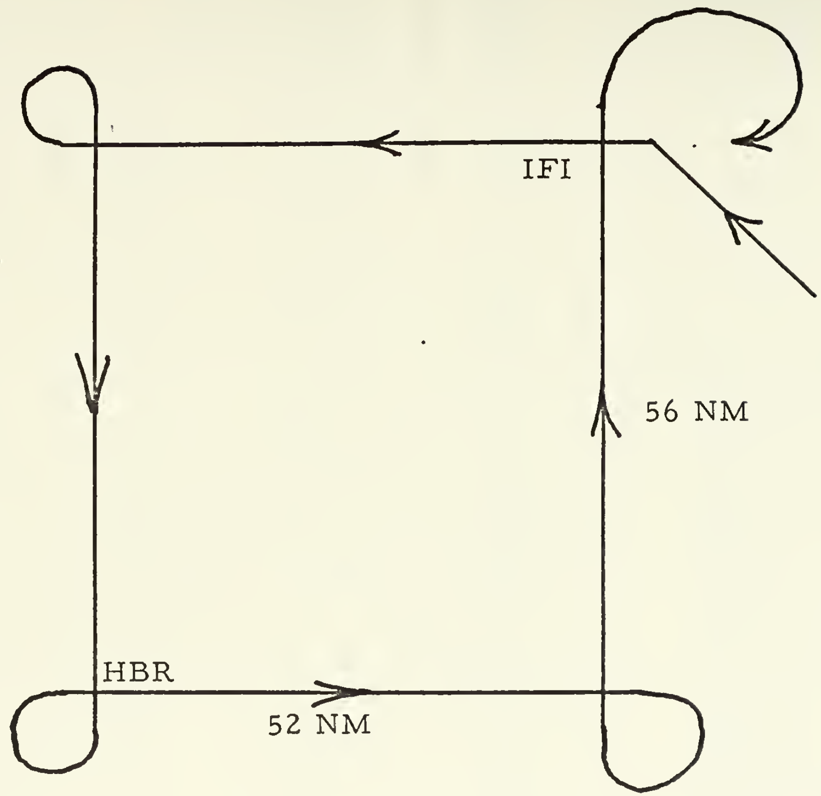


Figure 10. Recommended flight pattern in Oklahoma for data accumulation to determine navigation correction factors due to terrain and wind.

A valuable aid to re-navigation computations would be mounting a downward-looking camera in the aircraft. Repeater indications of angle of attack and angle of bank should be mounted such that they would be visible in terrain photographs along with synchronous time. Photographs need not be continuous but enough should be taken each 15 or 20 minutes to assure photographing an identifiable terrain feature. A means should also be provided whereby the navigator can activate the camera to record initial and terminal fixes, turning points or other desired locations.

For present operations, frequent accurate navigation fixes are required of the navigator, particularly during thunderstorm cell investigations. Cell investigations should be a series of straight line tracks between known fixes, but if long, shallow turns are used it is imperative that frequent and accurate aircraft positions be observed to allow for reconstruction of the flight path.

A properly configured aircraft with a trained crew is a valuable tool for augmenting a rawinsonde network and for specifying spatially nonuniform gradients in support of research on mesoscale phenomena. Based on RFF and rawinsonde capabilities and supported by the results of this investigation, a rawinsonde network and accompanying flight plans to provide coverage for mesoscale research in Oklahoma are suggested. The recommended rawinsonde network consists of the stations listed in Table A6 (Appendix A) which are depicted geographically in Figures 11a-c. This arrangement of nine stations provides

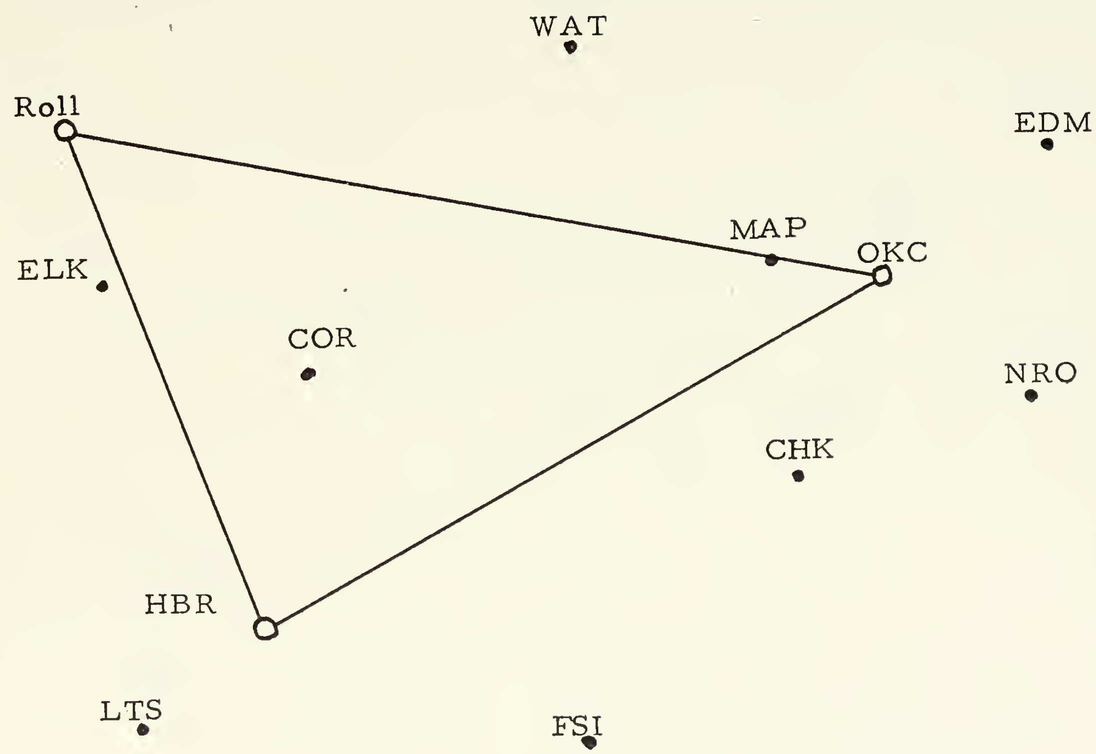


Figure 11a. Route A for aircraft operations associated with a nine-station rawinsonde network.

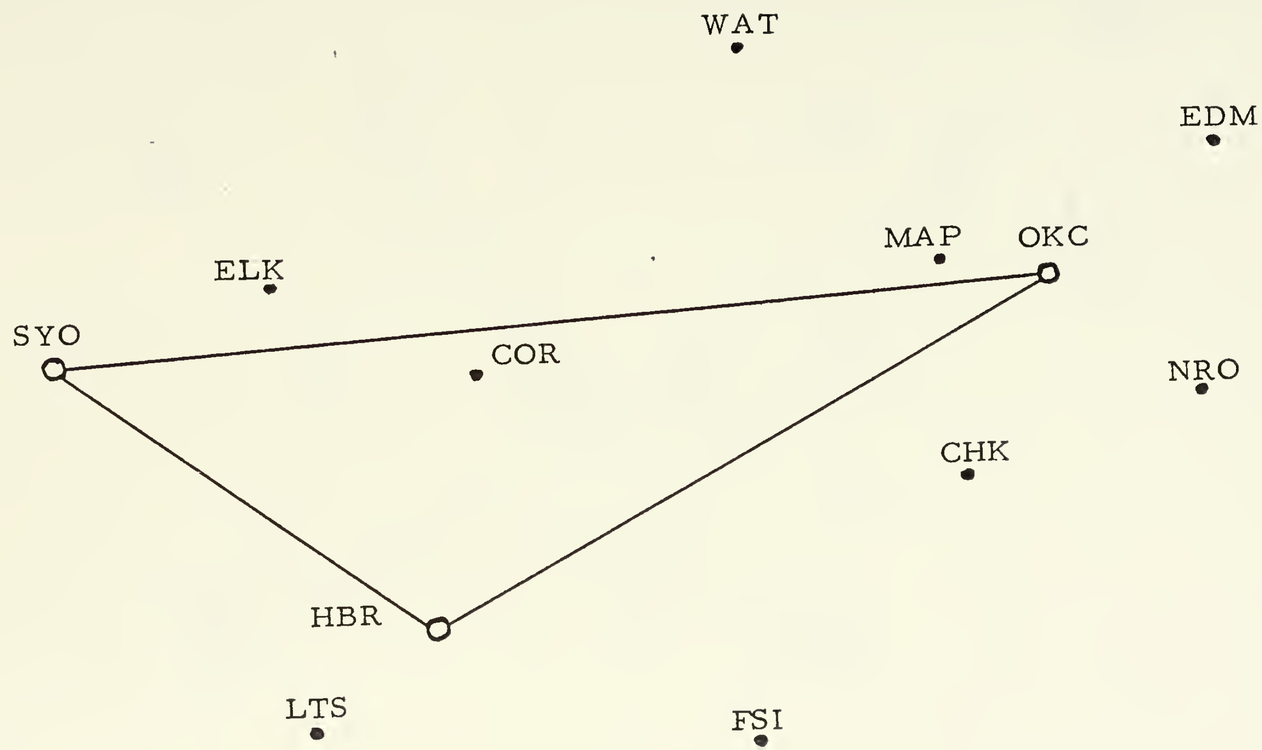


Figure 11b. Route B for aircraft operations associated with a nine-station rawinsonde network.

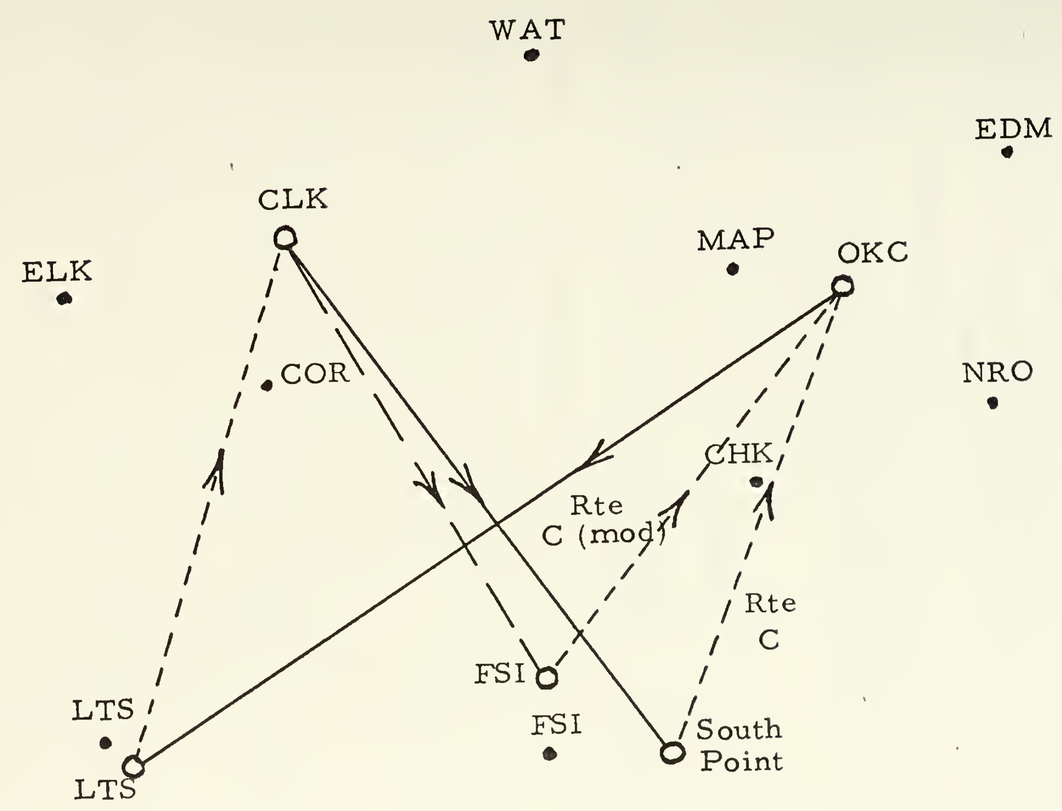


Figure 11c. Route C and modified route C for aircraft operations associated with a nine-station rawinsonde network.

excellent distribution for coverage within 100 nautical miles to the west of Norman.

Three recommended flight routes are described in Table 4 and depicted in Figures 11a-c. The recommended tracks are designed to provide diversified coverage but are not intended to be all-inclusive. Simultaneous rawinsonde launches from all stations would be conducted once each hour (or as directed) such that the aircraft is in the best location to take measurements in the vicinity (or predicted region) of developing convective activity.

Flight Routes A and B, oriented on established airways, lend themselves to an all-weather capability. Route C has legs oriented parallel and perpendicular to the expected approach path of thunderstorm cells and may be modified as depicted in Figure 11c or in any other manner to yield shorter legs. Provisions for tracks designed to investigate storm cells may be incorporated into the recommended routes or as separately designed routes. Departures from the planned tracks to avoid penetration of convective cells can be made, but navigation fixes must be obtained when leaving and returning to track and at points in between to allow reconstruction of the flight. All routes may be flown at any altitude or flight level although the standard levels of 850, 700 and 500 mb are most likely to be used. Navigation locating Roll intersection and South Point (Figs. 11a and 11c) may be difficult at low altitudes due to terrain interference, but two important points must be remembered:

Table 4. Description of recommended routes for project flights involving coordinated nine-station rawinsonde network

ROUTE A

To	Route	Distance	Notes
Roll Intersection	V210	86	1, 2
Hobart VOR (HBR)	Direct	55	
Okla. City (OKC)	V14	73	
	Total	214	

ROUTE B

To	Route	Distance	Notes
Sayre VOR (SYO)	V272	92	1
Hobart VOR (HBR)	Direct	40	
Okla. City (OKC)	V14	73	
	Total	205	

ROUTE C

To	Route	Distance	Notes
Altus TACAN (LTS)	Direct	87	1
Clinton Rbn (CLK)	Direct	55	
South Point	Direct	64	3, 4
Okla. City (OKC)	V77	50	
	Total	256	

ROUTE C (Modified)

To	Route	Distance	Notes
Altus TACAN (LTS)	Direct	87	1
Clinton Rbn (CLK)	Direct	55	
N. Fort Sill NDB (FSI)	Direct	52	4
Okla. City (OKC)	Direct	49	
	Total	243	

Notes:

1. Initial point - OKC
2. If at low alt monitor nav to avoid Washita Nat'l Wildlife Refuge 2.4 NM left of track 74 NM from OKC
3. 193° radial OKC, 50 NM
4. Avoid flying into Restricted Area R-5601A

1. frequent and accurate visual or radio navigation fixes must be taken;

2. maintaining the flight tracks of the described routes and overflying the planned fixes are not nearly as important as accurately fixing the aircraft's position.

Route A or Route B can be comfortably flown in approximately 5 hours and 40 minutes from takeoff to landing, each flight consisting of complete circuits at 850, 700 and 500 mb. In addition to the time required to fly each leg, conservative estimates of the time to perform the remaining portions of the flight are:

20 min.	initial climbout from Tinker AFB to OKC and equipment checks, if required;
5 min.	each turn at 850 and 700 mb, performed so as to pass over a navigation fix on course to the next fix;
10 min.	each turn at 500 mb, performed as above;
20 min.	climb from 850 to 700 mb;
30 min.	climb from 700 to 500 mb;
50 min.	descent from 500 mb and approach to landing.

Three circuits for route C at the standard levels would require approximately 6 hours and 15 minutes from takeoff to landing.

It has been shown that aircraft can be used to extend a rawinsonde network and define gradients between stations, but the full potential of a complete and accurate coordinated system has not been approached.

This investigation hopefully provides a step toward realizing the entire potential of aircraft in mesoscale research.

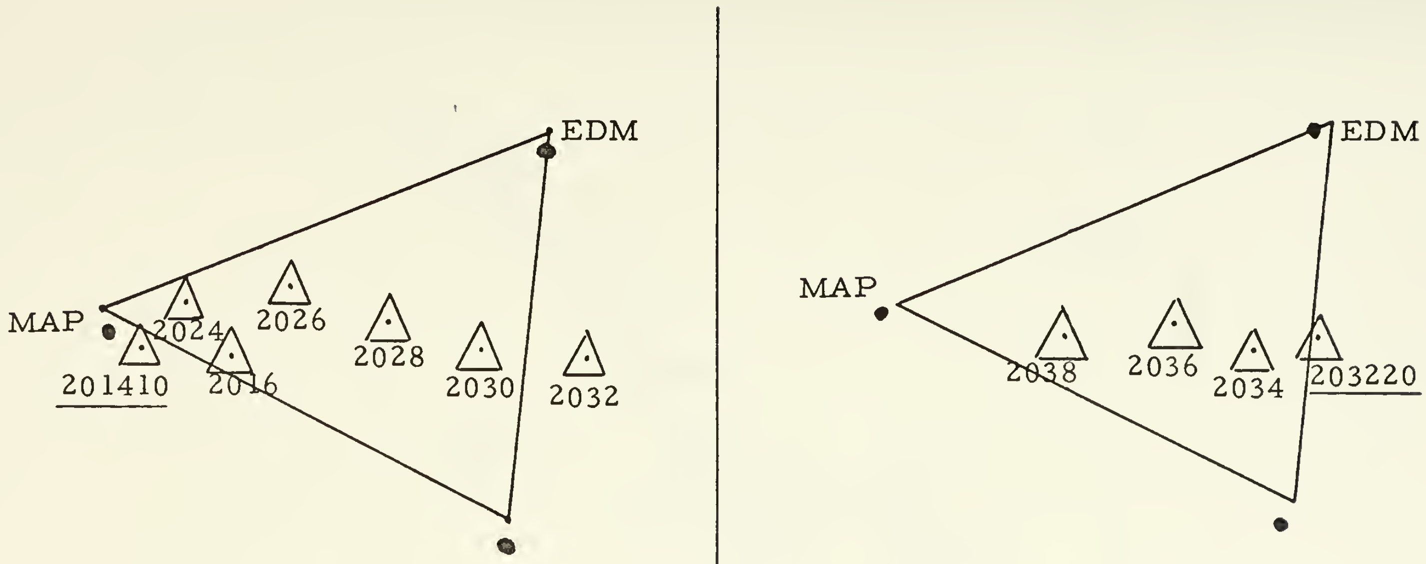
APPENDIX A

SUPPLEMENTARY DATA AND INFORMATION

1. GENERAL

Tables and figures included in Appendix A are detailed results of the investigation. Figures illustrating the comparisons of winds (A3a and A3b), temperatures (A4) and mixing ratios (A5) derived from aircraft and rawinsonde data are also depicted in numerical tables (A2a-d, A4a and A4b, A5a and A5b). The locations, relative to the rawinsonde network, of most of the 27 comparative data points are presented in Figures A1 and A2. Table A3 describes the characteristics of three sets of navigation tracks used for opposite track wind comparisons, and the geographic locations of the stations comprising the nine-station rawinsonde network are outlined in Table A6.

To demonstrate the selection of primary and secondary data points, the data points of 5 and 17 May at 850 mb are depicted in Figure A1 (primary data points are underlined). The large triangles outline the rawinsonde locations at 850 mb at the time associated with the primary data points. Figure A2 illustrates the horizontal path of the aircraft during the descent from 500 mb, the locations of the comparative data points and the associated rawinsonde paths.



17 May 1971 850 mb

5 May 1971 850 mb

Figure A1. Locations of selected primary and secondary comparative data points.

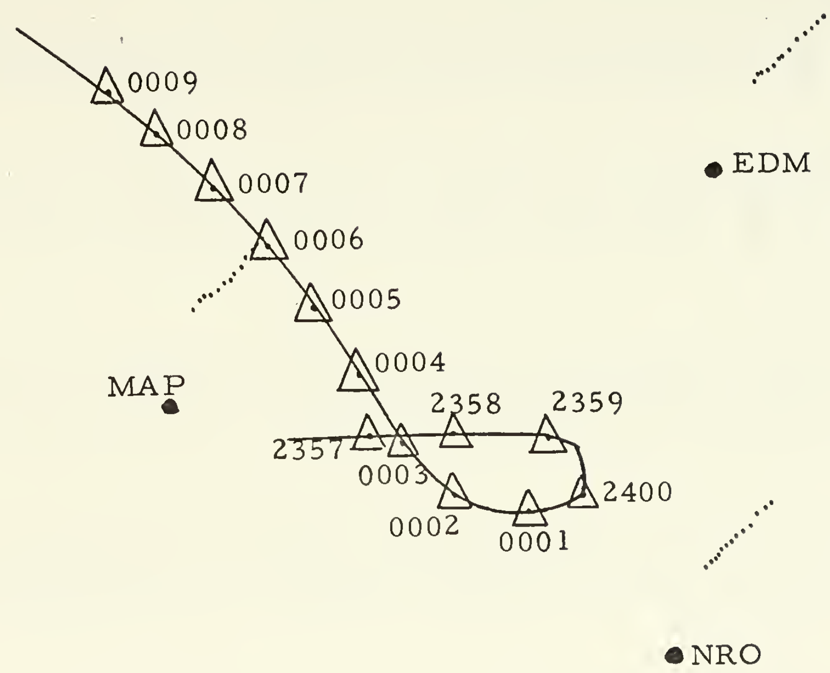


Figure A2. Aircraft flight path and rawinsonde tracks during comparative sounding 17 May 1971.

Table A1. Drift angle correction from RFF WINDS program compared with final drift angle correction required to correct latitude and distance traveled count correction required to correct longitude. Changes in ground speed and true airspeed as a result of application of distance traveled count correction and true airspeed correction factor are given in the last two columns.

Track	Level	Dir.	WINDS Program DACOR	DACOR	DTCOR	Change (Kts) GS	TAS
5-2	850	West	-0.35	0.81	1.019	3.4	3.6
5-3	850	West	-0.35	1.68	1.028	5.0	5.5
5-4	700	East	0.09	0.92	1.010	2.4	2.1
5-5	700	East	0.09	0.01	1.003	0.7	0.6
5-6	500	West	1.32	1.68	1.011	2.0	2.5
9-1	860	West	NA	1.42	1.024	4.6	4.8
9-2	805	West	NA	-0.13	1.018	3.2	3.5
9-3	805	East	NA	-0.65	1.012	2.6	2.4
9-4	780	East	NA	-0.18	1.012	2.6	2.3
9-5	750	East	NA	-3.13	0.969	-6.9	-6.1
17-1	850	West	0.30	1.30	1.030	5.5	5.8
17-3	850	East	0.50	-0.26	1.012	2.4	2.3
17-4	850	East	0.71	-0.47	1.015	3.0	3.9
17-5	700	West	0.23	1.61	1.011	2.0	2.3
17-6	700	West	0.58	1.09	0.995	-0.9	-1.0
17-7	500	East	1.02	1.39	0.978	-5.7	-4.9
18-1	850	West	0.15	1.18	1.028	5.0	5.4
18-2	850	East	0.05	0.36	1.012	2.6	2.5
18-3	850	East	0.05	-0.88	1.001	0.2	0.2
18-4	700	West	-0.39	0.87	1.016	2.9	3.3

2. WIND

Tables A2a-d describe the wind speed and direction obtained from the various navigation corrections. Probable upper and lower values computed as described in Table 2 are included for selected navigation correction schemes. Figures A3a and A3b are graphical displays of wind direction and speed respectively of seven representative data points taken from Tables A2a-d.

Probable upper and lower limits are not included for uncorrected winds or for winds obtained from navigation with all corrections except the final true airspeed correction, since the values of these two winds are used only to help describe the progression of changes to the winds as navigation corrections are applied. These two winds are plotted in Figures A3a and A3b on the same line and labeled as they appear from left to right.

Date	Time	Level	R PLV	R DD	R PUV	AFC PLV	AFC DD	AFC PUV	AGC DD	AWC PLV	AWC DD	AWC PUV	AU DD
5-5	203220	850	217	222	227	215	221	226	215	220	225	230	223
5-5	203400	850	217	222	227	212	218	225	212	217	223	229	222
5-5	203600	850	217	222	227	217	224	230	218	223	229	235	228
5-5	203800	850	216	221	226	223	229	236	226	231	237	243	235
5-9	205500	734	221	226	231	205	210	215	204		NA		231
5-17	201410	850	192	197	202	193	198	203	202	194	199	204	199
5-17	201600	850	192	197	202	193	198	203	202	194	199	205	199
5-17	202400	850	192	197	202	193	198	204	203	196	202	208	200
5-17	202600	850	192	197	202	192	197	202	202	193	199	205	199
5-17	202800	850	193	198	203	192	197	202	202	190	196	203	197
5-17	203000	850	194	199	204	195	200	205	205	196	202	208	201
5-17	203200	850	195	200	205	196	201	206	206	198	203	209	202
5-17	221413	700	216	221	226	208	213	218	210	212	218	224	219
5-18	203210	702	209	214	219	206	211	216	207	211	216	220	214

R - Rawinsonde
AFC - Aircraft, Full Correction
AWC - Aircraft WINDS Correction Only
AU - Aircraft, Uncorrected

PLV - Probable Lower Value
PUV - Probable Upper Value
AGC - Aircraft, all corrections except final TAS

Table A2a. Wind Direction from Rawinsonde and Aircraft Measurements with Probable Range for 14 Primary and Secondary Comparative Data Points.

R Time	Acft Time	Level	R PLV	R DD	R PUV	AFC PLV	AFC DD	AFC PUV	AGC DD	AWC PLV	AWC DD	AWC PUV	AU DD
235123	000900	700.5	231	236	241	231	238	244	238	232	239	246	240
235129	000800	698.2	230	235	240	228	234	240	234	228	235	241	236
235207	000700	687.6	229	234	239	225	230	235	230	225	230	237	230
235229	000600	673.8	227	232	237	222	226	231	226	221	226	231	226
235310	000500	657.1	224	229	234	220	225	229	224	219	224	228	223
235350	000400	636.1	220	225	230	223	227	231	227	222	226	231	225
235420	000300	615.1	218	223	228	222	226	230	226	221	225	230	225
235532	000200	592.8	219	224	229	217	221	225	222	218	222	226	223
235607	000100	576.6	220	225	230	216	220	224	221	217	222	226	223
235651	000000	557.7	222	227	232	227	232	236	230	225	228	232	226
235741	235900	536.3	224	229	234	227	231	235	229	224	228	232	225
235836	235800	514.5	226	231	236	228	232	236	230	224	229	233	226
235915	235700	501.1	227	232	237	234	238	243	236	230	234	239	232

R - Rawinsonde
AFC - Aircraft, Full Correction
AWC - Aircraft, WINDS Correction Only
AU - Aircraft, Uncorrected

PLV - Probable Lower Value
PUV - Probable Upper Value
AGC - Aircraft, all corrections except final TAS

Table A2b. Wind Direction from Rawinsonde and Aircraft Measurements with Probable Range for 13 Data Points in Comparative Sounding of 17 May 1971.

			R			AFC			AGC	AWC			AU
Date	Time	Level	PLV	FF	PUV	PLV	FF	PUV	FF	PLV	FF	PUV	FF
5-5	203220	850	23	28	32	29	32	35	29	25	28	31	28
5-5	203400	850	25	29	33	25	28	31	26	22	25	28	26
5-5	203600	850	25	30	34	25	28	31	26	22	25	28	26
5-5	203800	850	27	31	36	24	27	30	23	22	25	28	26
5-9	205500	734	21	25	29	32	35	38	29		NA		32
5-17	201410	850	25	29	34	33	36	39	37	30	33	36	35
5-17	201600	850	26	30	35	33	36	39	36	30	33	36	34
5-17	202400	850	26	31	35	31	34	37	35	26	30	32	32
5-17	202600	850	27	32	37	31	34	37	34	26	29	32	32
5-17	202800	850	27	32	37	31	34	37	33	27	30	33	32
5-17	203000	850	28	33	38	33	36	39	36	28	31	34	34
5-17	203200	850	29	34	39	34	37	40	37	29	32	35	34
5-17	221413	700	32	37	43	31	34	37	33	27	30	33	30
5-18	203210	702	38	45	51	35	38	41	35	31	34	37	35

R - Rawinsonde
AFC - Aircraft, Full Correction
AWC - Aircraft, WINDS Correction Only
AU - Aircraft, Uncorrected

PLV - Probable Lower Value
PUV - Probable Upper Value
AGC - Aircraft, all corrections except final TAS

Table A2c. Wind Speed from Rawinsonde and Aircraft Measurements with Probable Range for 14 Primary and Secondary Comparative Data Points.

R	Acft			R			AFC		AGC		AWC		AU
Time	Time	Level	PLV	FF	PUV	PLV	FF	PUV	FF	PLV	FF	PUV	FF
235123	000900	700.5	32	38	43	26	29	32	28	24	27	30	24
235129	000800	698.2	31	37	42	27	30	33	29	25	28	31	25
235207	000700	687.6	31	36	42	33	36	39	35	31	34	37	31
235229	000600	673.8	30	36	41	36	39	42	38	33	36	39	34
235310	000500	657.1	33	39	45	40	43	46	42	37	40	43	37
235350	000400	636.1	34	40	47	40	43	46	42	37	40	43	37
235420	000300	615.1	38	44	51	40	43	46	42	37	40	43	38
235532	000200	592.8	38	45	52	42	45	48	44	39	42	45	40
235607	000100	576.6	38	44	51	42	45	48	45	40	43	46	41
235651	000000	557.7	37	44	51	41	44	47	45	43	46	49	49
235741	235900	536.3	37	44	50	41	44	47	45	44	47	50	49
235836	235800	514.5	36	43	49	38	41	44	42	40	43	46	45
235915	235700	501.1	35	41	47	37	40	43	41	39	42	45	44

R - Rawinsonde
AFC - Aircraft, Full Correction
AWC - Aircraft, WINDS Correction Only
AU - Aircraft, Uncorrected

PLV - Probable Lower Value
PUV - Probable Upper Value
AGC - Aircraft, all corrections except final TAS

Table A2d. Wind Speed from Rawinsonde and Aircraft Measurements with Probable Range for 13 Data Points in Comparative Sounding of 17 May 1971.

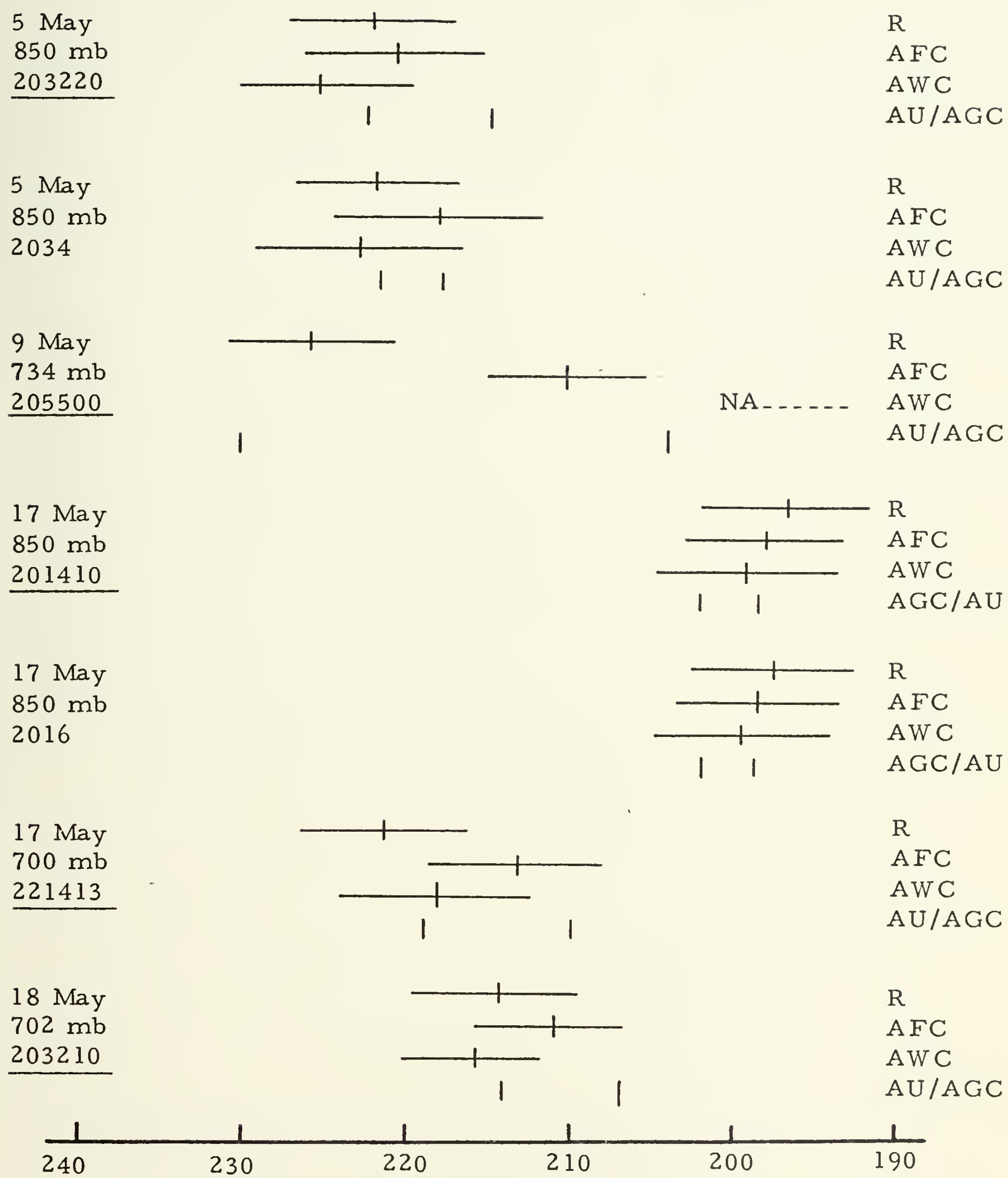
Table A3. Characteristics of three sets of consecutive navigation tracks suitable for opposite track wind comparisons.

Date	TBT	TT	Level	Remarks
5 May 1971	23+20*	43+20	850	Tracks coincide
9 May 1971	6+00	28+10	850	Eastbound track 2-5 NM south of Westbound
17 May 1971	8+50	32+00	850	Tracks coincide

TBT - Time Between Tracks; the time in minutes and seconds from the end of the first navigation track to the beginning of the second

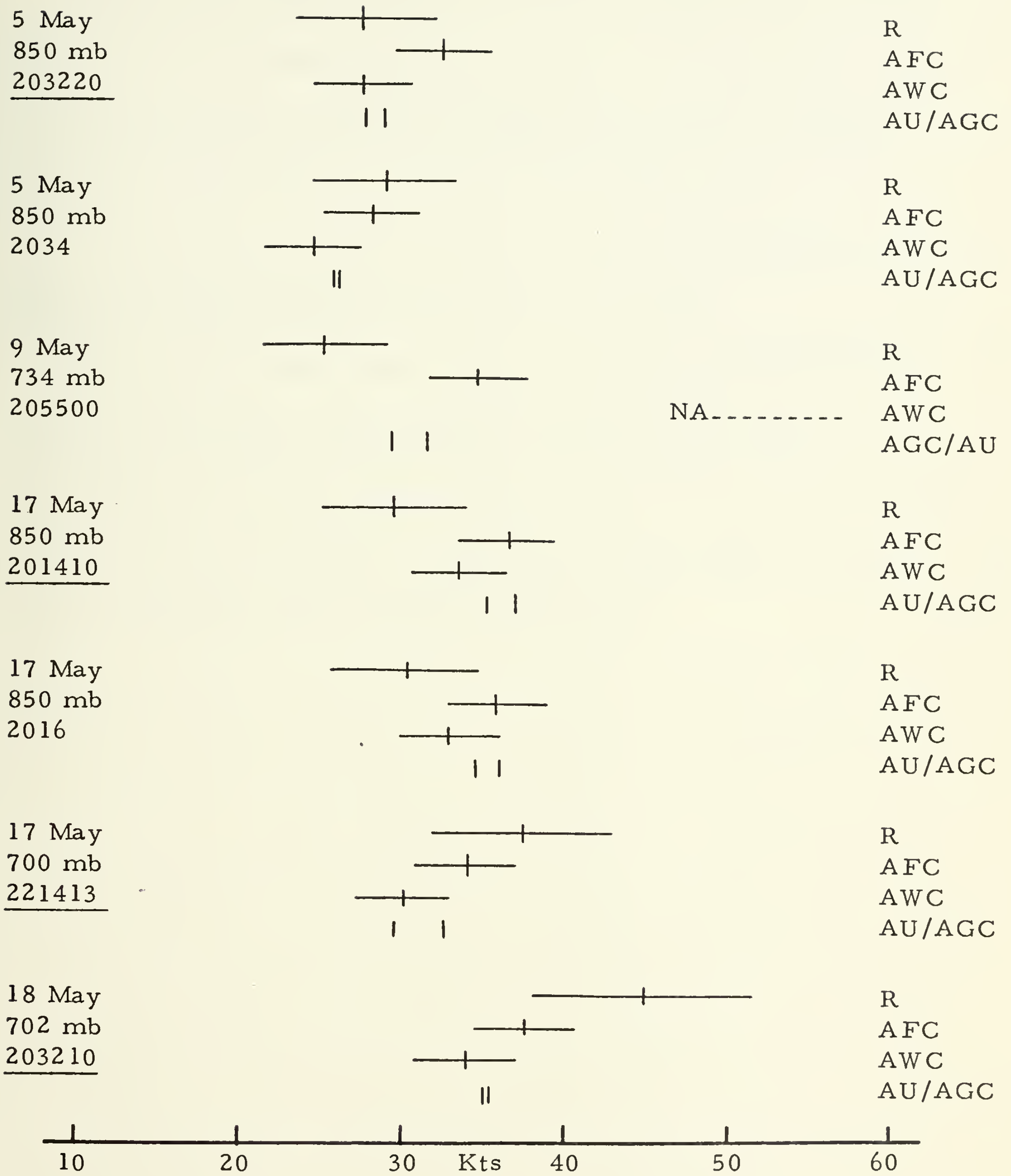
TT - Total Time; the time from the initial point on the first track to the final point on the second track

* The large TBT for this case is due to a winds calibration (Station 5-1, Table 1) that was performed between consecutive tracks. Since the winds during the calibration were relatively steady and since no mesoscale systems were present, it was reasonable to assume that the winds prior and subsequent to the calibration were relatively constant.



R - Rawinsonde
AFC - Aircraft, full corrections
AGC - Aircraft, all corrections except final TAS
AWC - Aircraft, WINDS corrections only
AU - Aircraft, uncorrected

Figure A3a. Wind direction from rawinsonde and aircraft measurements for seven representative data points.



R - Rawinsonde
AFC - Aircraft, full corrections
AWC - Aircraft, WINDS corrections only
AGC - Aircraft, all corrections except final TAS
AU - Aircraft, uncorrected

Figure A3b. Wind speed from rawinsonde and aircraft measurements for seven representative data points.

3. TEMPERATURE AND MIXING RATIO

Temperature values for the 27 comparative data points obtained from rawinsonde and aircraft measurements and their probable upper and lower values are tabulated in Tables A4a and A4b. Similarly, mixing ratio values appear in Tables A5a and A5b. Seven representative data points were selected from the temperature and mixing ratio tables and plotted in Figures A4 and A5 respectively.

The last three data points in Figure A4 are the primary and two secondary data points pictured in the left hand side of Figure A1. Examination of the temperature measurements at the three data points discloses the deterioration of temperature comparisons as distance and time increase away from the primary point.

			RAWINSONDE			VORTEX			ROSEMOUNT		
Date	Time	Level	PLV	R	PUV	PLV	TV	PUV	PLV	TR	PUV
5-5	203220	850	19.4	20.4	21.4	18.8	19.8	20.8	17.9	18.9	19.9
5-5	203400	850	19.4	20.4	21.4	18.2	19.2	20.2	17.3	18.3	19.3
5-5	203600	850	19.6	20.6	21.6	17.8	18.8	19.8	16.9	17.9	18.9
5-5	203800	850	19.7	20.7	21.7	17.8	18.8	19.8	16.6	17.6	18.6
5-9	205500	734	7.0	8.0	9.0	8.1	9.1	10.1	7.8	8.8	9.8
5-17	201410	850	16.6	17.6	18.6	16.5	17.5	18.5	15.4	16.4	17.4
5-17	201600	850	17.6	18.6	19.6	16.1	17.1	18.1	15.8	16.8	17.8
5-17	202400	850	17.8	18.8	19.8	16.4	17.4	18.4	16.2	17.2	18.2
5-17	202600	850	19.5	20.5	21.5	16.0	17.0	18.0	14.8	15.8	16.8
5-17	202800	850	20.0	21.0	22.0	17.8	18.8	19.8	15.8	16.8	17.8
5-17	203000	850	20.7	21.7	22.7	18.3	19.3	20.3	15.3	16.3	17.3
5-17	203200	850	21.7	22.7	23.7	20.1	21.1	22.1	17.0	18.0	19.0
5-17	221413	700	10.2	11.2	12.2	10.0	11.0	12.0	9.1	10.1	11.1
5-18	203210	702	2.8	3.8	4.8	2.6	3.6	4.6	1.9	2.9	3.9

PLV - Probable Lower Value
PUV - Probable Upper Value

Table A4a. Temperature from Rawinsonde Measurements, Vortex Temperature and Rosemount Temperature for 14 Primary and Secondary Comparative Data Points for 5, 9, 17 and 18 May 1971.

R Time	Acft Time	Level	RAWINSONDE PLV	RAWINSONDE R	RAWINSONDE PUV	VORTEX PLV	VORTEX TV	VORTEX PUV	ROSEMOUNT PLV	ROSEMOUNT TR	ROSEMOUNT PUV
235123	000900	700.5	9.9	10.9	11.9	8.5	9.5	10.5	8.0	9.0	10.0
235129	000800	698.2	9.7	10.7	11.7	8.4	9.4	10.4	7.9	8.9	9.9
235207	000700	687.6	8.8	9.8	10.8	7.8	8.8	9.8	7.3	8.3	9.3
235229	000600	673.8	7.0	8.0	9.0	6.9	7.9	8.9	6.0	7.0	8.0
235310	000500	657.1	5.1	6.1	7.1	5.2	6.2	7.2	4.2	5.2	6.2
235350	000400	636.1	2.8	3.8	4.8	3.5	4.5	5.5	1.8	2.8	3.8
235420	000300	615.1	0.5	1.5	2.5	2.0	3.0	4.0	0.4	1.4	2.4
235532	000200	592.8	-2.1	-1.1	-0.1	-0.3	0.7	1.7	-2.4	-1.4	-0.4
235607	000100	576.6	-4.4	-3.4	-2.4	-2.3	-1.3	-0.3	-4.4	-3.4	-2.4
235651	000000	557.7	-6.6	-5.6	-4.6	-5.4	-4.4	-3.4	-6.9	-5.9	-4.9
235741	235900	536.3	-8.8	-7.8	-6.8	-7.8	-6.8	-5.8	-9.1	-8.1	-7.1
235836	235800	514.5	-11.5	-10.5	-9.5	-10.3	-9.3	-8.3	-11.8	-10.8	-9.8
235915	235700	501.1	-13.3	-12.3	-11.3	-11.3	-10.3	-9.3	-13.4	-12.4	-11.4

PLV - Probable Lower Value
PUV - Probable Upper Value

Table A4b. Temperature from Rawinsonde Measurements, Vortex Temperature and Rosemount Temperature for 13 Comparative Data Points of the 17 May 1971 Comparative Sounding.

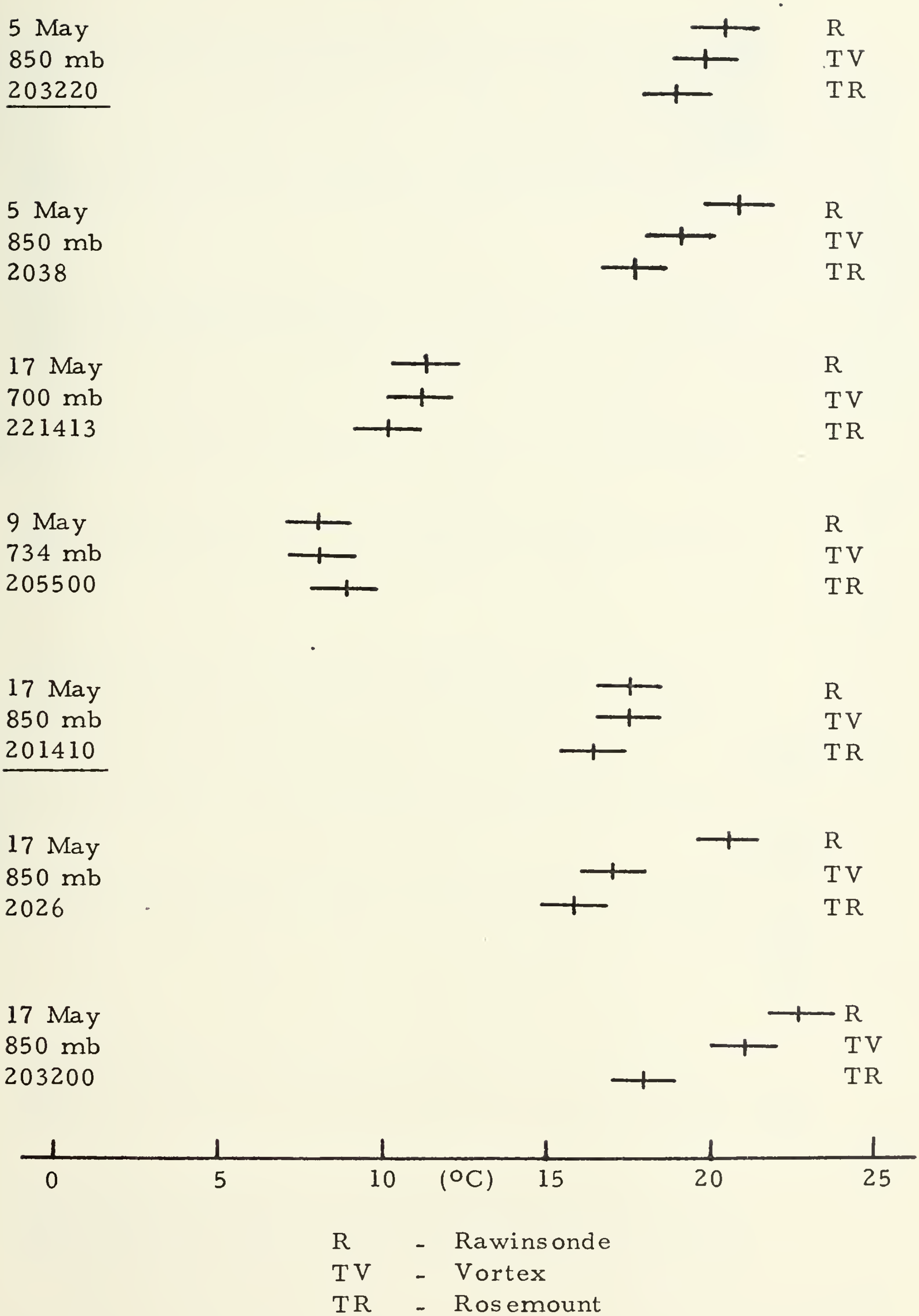


Figure A4. Temperature from rawinsonde and aircraft measurements for seven representative data points.

			RAWINSONDE			IRH			CSI		
Date	Time	Level	PLV	R	PUV	PLV	MI	PUV	PLV	MC	PUV
5-5	203220	850	3.04	3.96	4.87	1.9	2.0	2.1	2.1	2.5	2.9
5-5	203400	850	3.02	3.96	4.90	2.0	2.1	2.2	2.2	2.6	3.0
5-5	203600	850	2.64	3.55	4.48	1.9	2.0	2.2	2.3	2.6	3.1
5-5	203800	850	2.38	3.30	4.23	2.1	2.2	2.3	2.3	2.7	3.1
5-9	205500	734	4.22	4.67	5.14	4.4	4.6	4.8	4.1	4.8	5.5
5-17	201410	850	5.67	6.44	7.18	9.1	9.6	10.2	8.7	10.0	11.4
5-17	201600	850	5.77	6.59	7.40	8.5	9.0	9.5	8.7	9.9	11.3
5-17	202400	850	5.29	6.14	7.00	8.2	8.6	9.1	8.1	9.3	10.6
5-17	202600	850	5.16	6.09	7.03	9.3	9.8	10.3	8.8	10.1	11.5
5-17	202800	850	5.50	6.47	7.43	7.4	7.9	8.3	6.6	7.6	8.7
5-17	203000	850	5.77	6.78	7.77	8.8	9.3	9.8	8.4	9.6	10.9
5-17	203200	850	5.92	6.96	8.04	7.0	7.4	7.8	6.3	7.2	8.3
5-17	221413	700	2.49	3.10	3.70	4.1	4.4	4.6	6.0	6.9	7.9
5-18	203210	702	2.89	3.25	3.61	7.7	8.1	8.6	7.6	8.7	10.0

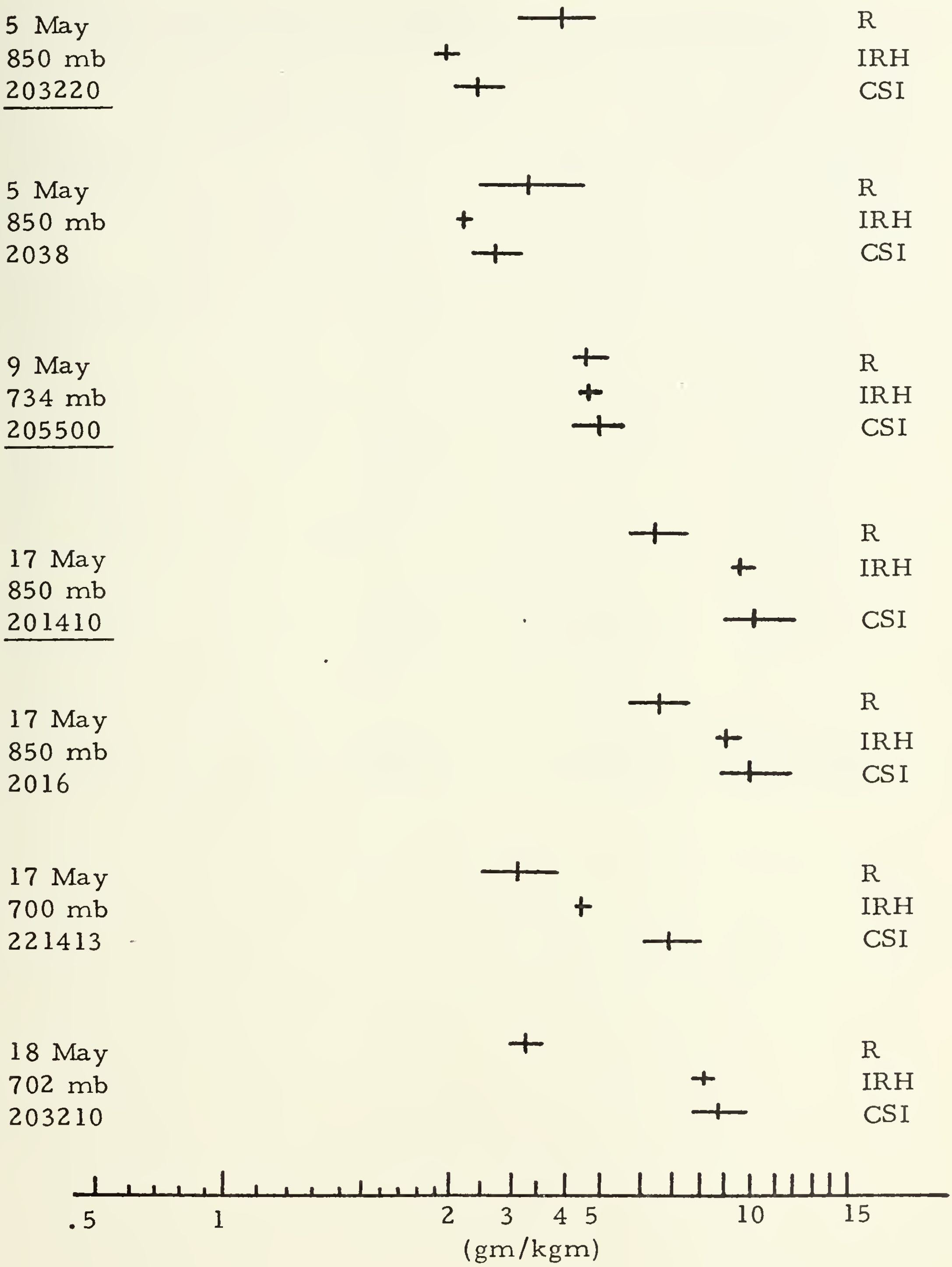
PLV - Probable Lower Value
PUV - Probable Upper Value

Table A5a. Mixing Ratio Calculated from Rawinsonde Measurements, Infrared Hygrometer and Cambridge Systems Dew Point Hygrometer for 14 Primary and Secondary Comparative Data Points for 5, 9, 17 and 18 May 1971.

R	Acft		RAWINSONDE			IRH			CSI		
Time	Time	Level	PLV	R	PUV	PLV	MI	PUV	PLV	MC	PUV
235123	000900	700.5	1.09	1.68	2.27	3.9	4.1	4.4	3.8	4.4	5.1
235129	000800	698.2	1.32	1.91	2.49	3.9	4.1	4.3	3.8	4.4	5.1
235207	000700	687.6	1.58	2.13	2.69	3.4	3.6	3.8	3.3	3.9	4.5
235229	000600	673.8	1.93	2.44	2.94	3.3	3.4	3.6	3.1	3.6	4.2
235310	000500	657.1	2.26	2.71	3.16	3.0	3.2	3.4	2.9	3.4	3.9
235350	000400	636.1	2.38	2.78	3.18	3.1	3.3	3.4	2.9	3.4	4.0
235420	000300	615.1	2.56	2.91	3.26	3.2	3.4	3.6	3.1	3.6	4.2
235532	000200	592.8	2.52	2.75	3.12	3.4	3.6	3.8	3.2	3.8	4.4
235607	000100	576.6	2.69	2.95	3.21	3.5	3.7	3.9	3.3	3.8	4.5
235651	000000	557.7	2.57	2.79	3.02	3.7	3.9	4.1	3.5	4.1	4.8
235741	235900	536.3	1.72	1.92	2.12	3.3	3.5	3.7	3.0	3.5	4.1
235836	235800	514.5	1.31	1.48	1.65	1.4	1.4	1.5	1.3	1.5	1.8
235915	235700	501.1	0.86	1.01	1.16	0.8	0.8	0.9	1.3	1.5	1.8

PLV - Probable Lower Value
PUV - Probable Upper Value

Table A5b. Mixing Ratio Calculated from Rawinsonde Measurements, Infrared Hygrometer and Cambridge Systems Dew Point Hygrometer for 13 Comparative Data Points of the 17 May 1971 Comparative Sounding.



R - Rawinsonde
IRH - Infrared Hygrometer
CSI - Cambridge Systems Dew Point Hygrometer

Figure A5. Mixing ratio from rawinsonde and aircraft measurements for seven representative data points.

Table A6. Nine station rawinsonde network for mesoscale investigation in conjunction with aircraft support flights.

Station	ID	Latitude	Longitude
Altus	LTS	34 42.0	99 19.8
Chickasha	CHK	35 06.1	97 57.7
Cordell	COR	35 18.0	98 58.2
Edmond	EDM	35 39.8	97 25.5
Elk City	ELK	35 25.5	99 23.0
Fort Sill	FSI	34 39.1	98 23.9
Mustang	MAP	35 28.6	98 00.5
Norman	NRO	35 14.5	97 27.6
Watonga	WAT	35 51.0	98 25.2

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13. ABSTRACT

Investigation of data obtained by aircraft during Project Rough Rider '71 reveals that aircraft navigation is unsatisfactory for mesoscale research on the convective cell scale. The established method for re-navigating the flights is modified to yield navigation errors of less than 0.1 nautical mile for most tracks when compared with entries in the navigator's log. It is shown that the corrections required are dependent on the height of the aircraft above the terrain, terrain slope and wind.

Meteorological parameters obtained from aircraft measurements are compared with rawinsonde measurements. These comparisons show that if appropriate corrections are applied, the data are useful for extending rawinsonde networks and defining spatial gradients of parameters between stations. Recommendations for determination of correction factors and suggestions for further research are made.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aircraft Data						
Rawinsonde Data						
Mesoscale						

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